A Roadmap for Education Technology

Beverly Park Woolf

A Roadmap for Education Technology

This work was supported by the Computing Community Consortium (CCC),
which is managed by the Computing Research Association (CRA)
and funded by the National Science Foundation (NSF).

This work was funded by the National Science Foundation # 0637190, The Computing Community Consortium (CCC), managed by the Computing Research Association (CRA) with a sub-award to Global Resources for Online Education, Beverly Park Woolf, P. I.

Global Resources for Online Education Workshop Authors

Beverly Park Woolf, *University of Massachusetts, Global Resources for Online Education, Chair*

Valerie Shute, *Florida State University*

Kurt VanLehn, *Arizona State University*

Winslow Burleson, *Arizona State University*

John Leslie King, *University of Michigan*

Dan Suthers, *University of Hawai'i*

Bert Bredeweg, *University of Amsterdam*

Rose Luckin, *London Knowledge Lab*

Ryan S. J. D. Baker, *Worcester Polytechnic Institute*

Emma Tonkin, *UKOLN & University of Bath*

For full list of Workshop Participants, see page 73.

Please send comments to bev@cs.umass.edu

Contents

About this Report

This report describes the initial findings of several workshops convened in 2009 to consider the future of education and in particular the role of technology and computer science in education. Through a series of facilitated collaborative workshops, leaders in several disciplines engaged in conversations that cast computers in the role of facilitating education in the future and recommended a research agenda for federal funding.

This project was guided by several fundamental values and beliefs, primarily the view that cyberspace can be a collaborative and cognitively supportive learning space and that global (online) education, based on customized teaching provides a powerful component of education for the 21st century. The participants suggested several pilot programs that should be funded to identify the education and technology challenges, for example, assessment and interoperability. They proposed coordinated pilot programs that provide concrete examples to inform our continuing discussions. Another belief is that the educational advances we propose can only be accomplished through intense, concerted, long-term efforts championed by federal agencies, led by committed researchers and involving breakthroughs in computational science, cognitive psychology, and the science of learning and education.

This report is not about predicting the future.

This report is not about predicting the future. Instead, our starting point was simply to consider some of the greatest challenges and opportunities for education in the 21st century. From there, we considered how computing and technology needs to, and can, play a vital role in realizing advances in education. Finally, we considered what needs to happen in computing and technology — as well as in education policy — to accelerate advances that can then help address key global challenges with a 20 year time horizon. Workshop participants identified educational needs, outlined perceived challenges, defined future impacts, and articulated a roadmap to achieve strong educational results.

This report articulates a comprehensive vision of education technology towards 2030 and identifies specifically what the education community and policy makers might do to realize that vision. Our hope is that this report serves to stimulate debate and discussion to refine the issues we articulate and others that we have not considered; that it galvanizes the technology and education communities into working more closely together and to provide input into and inform education policy thinking.

We encourage dialogue that underlines the importance of education in an information society, the and changing nature of basic education. We need to move the agenda beyond the currently limited 'e-learning' focus, which often replicates lectures, books and tests.

The report's emphasis is on the role and impact of computing and technology in education. It does not focus on other powerful developments that also influence education, notably the learning sciences and cognitive psychology. This is not to deny their importance. We deliberately chose to focus on the intersection of technology and education because of its importance for the future of education.

This report is the product of several facilitated meetings, together with months of analysis and discussion by the participants and others we consulted. The discussion groups involved over 40 researchers from several nationalities chosen for their expertise in particular fields, spanning computer science, psychology, and education, to name a few. These discussions were part of **Global Resources for Online Education** (GROE), a project sponsored by the National Science Foundation (NSF) and the Computing Community Consortium (CCC).[i] The primary mission of the GROE project was to envision the future of educational technology and to recommend research agendas for federal funding of that vision.

Paul Cohen of the University of Arizona began preliminary discussions on this topic during the Fall Symposium of the Association for the Advancement of Artificial Intelligence, November 7-9, 2008.[ii] The first workshop of the GROE Project was held in Tempe Arizona from April 23-26, 2009 at Arizona State University and a second forum was convened from July 4-5 2009 in Brighton, England.

This is our initial report and we will be refining it through public feedback and discussions generated by peers, others in the education community, and with policy makers. Your contribution is welcome, whether to build upon what we have done or to constructively criticize it.

We welcome feedback and critiques of this report. Any comments should be addressed to:

Beverly Park Woolf
Department of Computer Science
University of Massachusetts
Amherst, MA 01003
bev@cs.umass.edu

i. The Computing Community Consortium was created by the Computing Research Association to mobilize the research community to formulate important questions facing the field and develop strategies for pursuing them.

ii. See https://garuda.cs.arizona.edu/iicp/Fall_Symposium and http://iicp.cs.arizona.edu/submissions/

Summary

The next revolution in education will couple far more advanced computational technologies with far deeper knowledge about human cognition, including dramatically more effective constructivist and active instructional strategies. The impact of such a revolution will encompass not only new modes of learning and pedagogy, but new organizational systems for education. The purpose of the **Global Resources for Online Education** (GROE) initiative is to identify the next big computing ideas in education, to achieve open access of global educational resources and the reuse, repurposing, and sharing of such resources.

Our goals were to help inform the education policy debate and to ensure that today's children become tomorrow's educated citizens able to tackle key challenges and opportunities in the 21st century. The GROE project first identified seven educational challenges and then enumerated seven promising technologies that might be developed to meet those challenges.

In this section, we summarize the educational challenges, specifically *personalizing education, assessing student learning, supporting social learning, diminishing boundaries, developing alternative teaching strategies, enhancing the role of stakeholders,* and *addressing policy changes*. We also suggest opportunities for research and development of promising technologies, including *user models, mobile tools, networking tools, serious games, intelligent environments, educational data mining,* and *rich interfaces*.

We describe the results found, visions for the future and opportunities for research and funding. At the conclusion of each paragraph, we recognize the individuals who served as team leaders for discussions relating to the respective topics.

1. Personalizing Education

We suggest that in the next few decades education will be personalized to harmonize with each student's traits, for example, personality, learning style, and states, such as, affect,and level of engagement. Computational tools will understand an individual's strengths, weaknesses, challenges and motivational style as might a human tutor. Technologies available to produce such personalized instruction include user-models, intelligent environments, gaming environments, and data mining.

Research funding is needed to investigate:

- *learning models that represent what learners know and can do*. When and how was knowledge learned? What pedagogy worked best for a given learner?

- *machine learning and data mining techniques, including algorithms that are particularly adaptable to educational data.* How do we manage vast amounts of data, and effectively store, make available and analyze data for different purposes and stakeholders?

- *simulations and representations that explain themselves to learners.* How do we address the communicative interaction between learner and software, and use multimedia to switch modalities as appropriate?

(Team leaders: Kurt VanLehn, Arizona State University;
Bert Bredeweg, University of Amsterdam).

2. Assessing Student Learning

We believe that by 2030, assessment of students' knowledge, skills, and other attributes will be seamless and ubiquitous. Assessment will be available every time a student learns and will move beyond the current model of "Teach / Stop / Test." Seamless refers to the removal of false boundaries between learning and assessment, and ubiquitous refers to the constant nature of assessment that will feed back results and implications into learning, anywhere and anytime. The technology available to produce this result includes computational tools that model human competency; instructional databases; digital libraries; and educational data mining.

Research funding is needed to support studies that:

- *account for the full complement of characteristics brought to bear in learning*. What are learning competencies? How do they relate and how do we acquire evidence of them?

- *fuse assessment and learning*. What are new sources of assessment? How do they flow to, from and with learning; and how can we tear down conceptual and practical barriers between assessment and learning?

- *render assessments useful to all parties*. Who makes assessment decisions about learners? What information do they need; how does assessment provide evidence for those decisions; and how can we best communicate the complicated results of assessment to each party?

(Team Leader: Valerie Shute, Florida State University).

3. Supporting social learning

Socially embedded and social driven learning is pervasive. We no longer consider individual learners as learning in isolation. Currently students do work together in classrooms, but only during fixed time periods and

Future social learning will continue beyond the school day, will involve continuous input from team members and will be available wherever students are located.

with restricted team activities. Future social learning will continue beyond the school day, will involve continuous input from team members and will be available wherever students are located. Technology will sustain continuous learning by active students in a way that enable students to communicate where they are located and to value learning. Technologies that might address social learning include distributed instructional software, learning communities, networking, collaboration and mobile and ubiquitous computing to create seamless social learning.

Research funding is needed to support studies that:

- *examine how learning communities sustain, build on and share knowledge*. How do communities interact and share knowledge resources?

- *address infrastructure (API, management) and application level (representation) issues.* How can we achieve more than just technical interoperability and also support semantic interoperability? What integrations/mashups of devices/platforms would more effectively support social learning distributed across time, space and media?

- *treat the social group as a learning unit, but not to the exclusion of the individual.* What analyses are needed to relate individual and social learning?

(Team Leaders: Daniel Suthers, University of Hawai'i at Manoa; Rose Luckin, London Knowledge Lab).

4. Diminishing Boundaries

One long term goal is to re-examine, cross, mitigate and/or eliminate many of the artificial and non-productive boundaries that have been established within educational institutions, including place of study (home, work, institutions), education level (school, college, university and professional development), personal ability (special and typical students) and type of learning (formal and informal).

Education by 2030 has the potential to be seamless, ubiquitous and pervasive across place of study, educational level and type of learning. Technologies that might be applied toward seamless and ubiquitous learning include mobile systems, social networks, digitized artifacts, virtual computing from many computers and augmented physical space.

Research funding is needed to support studies that:

- *increase opportunities for learning outside, as well as inside the educational apparatus*. When does learning occur? How should learning outside of traditional academic settings, such as, at home and informally, be supported?

- *develop tools and resources for learning that are available across society.* How can we support seamless transition between formal and informal environments? How can students learn continuously?

(Team Leader: Emma Tonkin, UKOLN, University of Bath, UK).

5. Developing Alternative Teaching Modes

Education should prepare students to be citizens in the high-technology world of the 21st century where reasoning, disciplined thinking and teamwork are vital. Students will need to solve complex problems in innovative ways and think clearly about vast amounts of knowledge. They will work across disciplinary domains in collaboration and use inquiry reasoning. Technologies that can help to develop alternative teaching modes include rich computer interfaces, intelligent environments, learning companions, teachable agents, and tools that detect and respond to student emotion.

Research funding is needed to support studies that develop resources for:

- *collaborative inquiry as students become exposed to diverse cultures and viewpoints.* What is the process by which teams generate, evaluate, and revise knowledge?

- *enhancing students' communication skills and creative abilities.* Which tools match learners with other learners and/or mentors taking into account learner interests?

- *exploratory, social, and ubiquitous learning.* How can software both support collaboration and coach about content

(Team leader: Winslow Burleson, Arizona State University).

6. Enhancing The Role Of Stakeholders

Teachers will continue to be of primary importance in schools and will play new and different roles in connection with technological tools. As technology becomes more pervasive in education, stakeholders (teachers, students, parents, administrators and employers) will more effectively and consistently utilize it as part of instruction and in some cases integrate it fully into their teaching and learning. Stakeholders will trust educational technology to do what it claims to do and be assured that students have absolute privacy.

Research funding is needed to support studies that:

- *extend the teachers' significance to informal as well as formal settings and increases their interactions with students in broader and more diverse contexts.*
- *develop more tailored and higher quality information upon which teachers will base their decisions.*
- *address the historical imbalance between excitement for children vs. excitement for teachers in classrooms.* Which activities and environments make teachers' experiences as engaging and motivational and productive as children's experiences?

7. Addressing Policy Change

We expect global education based on customized teaching will be effective in the year 2030. A knowledge society at a global scale and magnitude requires people to learn rapidly and to quickly form new learning communities. In this context, education should be a civil right for all people.

It is naive to think that traditional policy reforms will result in the large-scale changes needed. Rather, broadly-based, systemic changes should be thought of as social movements. If the society is to embrace the scope and scale of needed changes, such social movements must be launched and sustained over protracted periods of time.

This report was produced contemporaneously with the production of another report that advocates similar support for the potential for information technology to transform education. *Transforming American Education: Learning Powered by Technology, the National Educational Technology Plan 2010 (NETP)* is discussed throughout this report, and is discussed in detail on page 38.

(Team leader: John Leslie King, University of Michigan).

Introduction

Laying the Ground

Over the past 40 years, educational technology has automated some of the more tedious tasks related to education, such as, providing databases of homework problems and recording grades. Rarely has education technology been challenged to provide for lifelong and lifewide learning or to support learners who are fully active through inquiry, collaboration and discussion.[54] Additionally, the tremendous advances that have been made in technology, for instance, mobile systems and social networks, have not yet been properly considered nor fully exploited for educational purposes, especially given their potential for seamless, ubiquitous, individualized and inclusive learning opportunities.

A series of facilitated workshops were conducted to articulate these opportunities and outline a path for developing potentially powerful educational tools and infrastructures. Leaders from several academic and professional disciplines engaged in creative conversations to investigate the role of computation and technology in education, covering such issues as the learning of core ideas, learning from simulations and virtual worlds, and the use of data management to support research and learning processes.

This report... lays out a roadmap to address the development of learning technologies that are relevant to current and future educational needs.

This report provides an overview of the discussions held during the GROE project. It lays out a roadmap to address the development of learning technologies that are relevant to current and future educational needs.

Significant educational change depends substantially on systemic processes and cultural effects, and requires participation, dialogue and cross-fertilization across a number of research disciplines, including social and political sciences. For the purpose of this document, research recommendations have been restricted to the fields of cognitive science, education, computer science and the learning sciences, with the assumption that there will be parallel efforts to identify and fund research in the other related areas, and with the understanding that implementing change also requires policy and funding activities beyond the boundaries of this research project. The NETP provides a useful summary of the motivating factors behind improving education.

Motivation for the work

Many countries have invested heavily in their existing educational apparatus and spend a great deal of money maintaining that investment. But research has provided comparatively little understanding of exactly how the educational apparatus may be improved to assure that it serves teachers and learners better with respect to the goal of educating all people (youth as well as adults), at all levels (school, college, professional development), across all locations (home, work, institutions) and in all types of activities (work, recreational and hobby-related). Without such research, it is impossible to learn how we might set directions that are both scalable and sustainable.[45]

This difficult challenge arises from an inherently complicated ecology. Learning and teaching are highly complex and time-consuming activities, requiring significant effort. Currently, teachers decide what is taught, identify and acquire resources, and infer the intentions and beliefs of their learners.[36] They alone are responsible for many of the teaching activities, for example, creating the learning opportunities, involving learners and providing intellectual and emotional support, as well as feedback and evaluation. In the US, emphasis on standardized testing leads teachers to teach to the test and not to apply what is learned to real-world problem-solving nor to true conceptual understanding.

Existing technology developed for business or recreation has been used in education, for example, text processing, cloud computing, and graphics production. Such technology was never designed to meet profound educational objectives, such as enabling students to explore, solve problems and learn,[14] and thus this software has not had a big impact on education.[54] Simply adopting "cool new technology" is not the proper starting point for much needed stakeholder-oriented solutions.

A more *intentional* approach toward educational technology asks how to support and enhance fundamental educational innovation through technology. To authentically address the future of education requires that we approach the educational ecology from the perspective of teachers, learners and other stakeholders. This intentional view starts from this perspective and identifies how technology can be challenged to produce such transformations.[54] Teachers struggle rather desperately to maintain the conventional methods on which their institutions run; they also attempt to use technology to transform the way they teach. Some don't even try.[54] It is crucial to identify "what teachers need in order to do the tough job of helping learners understand difficult ideas and develop high-level skills. And then use this to challenge the technology to come up with something *better* than what is now envisioned."[54]

It is also important to study which education innovations benefit which individual learners. Students need support in the social aspects of learning and in using a variety of exploratory and inquiry tools. This can be accomplished through agents, simulations and artificial intelligence methods that model and systematically represent instructional methods, scaffold learners and support student exploration. Students should be supported to search for a wide variety of information, connect to the real world, gather and analyze data, and communicate through a variety of social channels. Similar thinking should be applied to all other stakeholder groups: administrators, parents, and other interested individuals in business, industry, nonprofit organizations and government agencies who use technology to develop new and more specialized skills in the workforce.

The GROE Project sought to identify promising lines of inquiry toward developing socio-technological solutions for addressing complex learning and teaching problems, both in the context of formal education in traditional school settings, and in informal learning that takes place outside of the classroom. This project brought together a broad range of stakeholders,reflecting a wide spectrum of constituent experts who are making an effort to identify the needs of society as a whole. The resulting thought experiments helped identify the next big ideas that might provide solutions to important but hard-to-solve problems regarding the future of education, and that shed light on how research investments and public support can be catalyzed to create a better educational future. Two broad challenges were thus addressed during the GROE project activities:

1) In what ways might computational technology be fully utilized in education to achieve the promise of open access to global resources and greatly enhanced and larger scale use of information technology in teaching and learning?

2) What is the research agenda for federal funding that can make this happen?

The Promise Of Education Technology

"The illiterate of the 21st century will not be those who cannot read and write but those who cannot learn, unlearn and relearn."

— Alvin Toffler, *Forward to Rethinking the Future*, 1971

In exploring the education-technology equation, the GROE Project first asked: "What are the grand challenges facing education?" and then, "What technologies show greatest promise to address those challenges?"

Table 1 *(below)* illustrates the relationship between the grand challenges of education and the potential of education technology needed to satisfy them. Each grand challenge (left) requires a combination of technology features (middle) for which we expect several resulting educational capabilities (right) to be in place by the year 2030.

To meet the educational challenges, we have selected seven information technologies that show great promise for educational innovation, specifically *user modeling, mobile technology, social networking tools, serious games, intelligent environments, data management* and *rich interfaces*. While many such technologies already exist in the laboratory, they have not been combined in large scale or in optimal ways for education.

The GROE Project explored current trends that support the intentional approach to improving education. Section A introduces several "grand challenges" in education that are in need of redress and that provide a backdrop for the potential of new and emerging technologies. Several key learning technologies are described in Section B and we explore how each technology can be pressed into service to address the educational grand challenges, along with research needed to enhance each technology.

Education's Grand Challenges

- Support intense active learning.
- Generate alternative *teaching* styles, e.g., inquiry, collaboration, discussion.
- Understand alternative *learning* approaches, e.g., gender, ability, ethnic.
- Personalize teaching.
- Diminish boundaries.
- Enhance role of stakeholders.
- Lifelong learning approaches
- Address policy challenges.

→

Technology Features

- Mobile systems
- Intelligent environments
- Remote access to information
- Student modelling
- Open-learner Models
- Choice-adaptive systems
- Assessment tools
- Data management tools
- Rich interfaces, e.g., sensors, agents.
- Multi-modal communication, e.g. speech, text, gesture
- Social networks
- Intelligent search engines

→

Education's Capabilities ~2030

- Global resources provide informed and appropriate teaching, e.g., support cognitive, meta-cognitive and affective learning.
- Learning is personalized, seamless and ubiquitous.
- Assessment is seamless and ubiquitous.
- Learning boundaries, e.g., place, time, style, are diminished
- Stakeholders role is enhanced with trustworthy and collaborative resources.
- Policy changes move towards universal learning.
- Teaching systems recognize and respond to alternative learning styles.

Table 1
Challenges, Technology, and Future Educational Capabilities

A. Grand Challenges Of Education

"We are not going to succeed [in education] unless we really turn the problem around and first specify the kinds of things students ought to be doing: what are the cost-effective and time-effective ways by which students can proceed to learn. We need to carry out the analysis that is required to understand what they have to do — what activities will produce the learning —and then ask ourselves how the technology can help us do that."

— Herbert Simon, *'What We Know About Learning,'* 1997

A society built on knowledge requires that its members acquire new skills quickly, engage in new learning approaches enthusiastically and form new learning communities that work well. For educators, this requires rapid revision in what is taught and how it is taught to take advantage of evolving knowledge in a field where technology changes every few years. As an ex-ample, the Internet first appeared for general use in the mid 1990s. As of 2009, an estimated quarter of Earth's population used its services and its countless applications are used in virtually every aspect of modern human life. How can educators teach topics that barely exist one day and within in a short time will change their students' lives? How do they teach about the next Internet-level change in society? In many cases there are no names today for fields that teachers will teach in the future. For example, online social networking has become immensely popular among today's school-aged children, yet they hardly existed in 2007.

The 21st century workforce needs both "hard" skills (in traditional disciplines, such as, history, mathematics, science) as well as "soft" skills (behavioral and social skills, including, teamwork, evaluating and analyzing information, computer literacy and presentation skills).[88] Students need to engage in experiences that are different from those engaged in by people generations ago. Yet many of today's classrooms look exactly like 19th and early 20th century classrooms; teachers use old methods, for example, lecturing to passive students and assigning memorization tasks to be solved by students working alone, that do not require the understanding and application of concepts to realistic problems.

Changes in educational policy, practice and administration tend to happen slowly. Development of qualified teachers takes much longer than most people realize.[45] It takes about 25 years from birth for an individual to receive a sufficiently well-rounded education to become a proficient educator. Years of additional experience are required before teachers learn how to work effectively in classrooms while keeping up with continual changes in accepted best practices. The impact of their teaching cannot be seen in subsequent learners for another 20 years. Thus the total cycle time for learning improvement is on the order of 45 to 50 years. Very few challenges in research or social policy cover such a long time scale. But failure to consider such time scales cripples our efforts to understand the systemic characteristics of the challenge. Indeed, it may be prudent to design adaptive approaches that do not require predicting the future so far.

One goal in applying technology to education is to address implications of cyberspace as a collaborative and cognitively supportive learning space.

One goal in applying technology to education is to address implications of cyberspace as a collaborative and cognitively supportive learning space. As we couple far more advanced computational technologies with far deeper knowledge about human cognition, we expect to enable dramatically more constructivist and active instructional strategies. Such a revolution will encompass not only new modes of learning pedagogy, but also new organizational systems for education.

This section identifies several emerging capabilities of education as a result of new technology. One goal is to achieve open access of global educational resources and to reuse, repurpose, and share such resources among all the people of the earth. We look both at the near-term (2 to 5 years) and at the twenty-year time frame. We expect future systems to harness the deluge of scientific and learning data flowing through them, monitor themselves (through machine learning) and raise new issues, for example dynamic student assessment, personalized feedback, lifelong learning, etc. We describe each of the seven educational challenges to be met by the year 2030, and conclude with a discussion of applications beyond traditional boundaries, in areas such as adult education and healthcare.

1. Personalizing Education

The first grand challenge in education is to *personalize education*. In the past, teachers had the exclusive authority to hold and dispense scarce instructional resources. The NETP makes this point by noting that learning in the past has been dominated by a "one size fits all" model, but that technology makes it possible to move to a new model of learning that breaks free from that constraint. Learning meant 'the acquisition of knowledge relevant to issues encountered in the world.'[50] Now, in the information age, individual learners are asked to shape their own knowledge out of their own sense of the world. Information is material selected by individuals to be transformed by them into knowledge to solve a problem in their life-world.[14] The demand made of individuals in the market-dominated society is nothing short of that of developing a new predisposition for learning, constantly seeing the life-world framed both as a challenge and as an environment and a potential resource for the individual's learning.[50]

This is a fundamental change from the past when individuals could rely on 'authorities' to decide what was important to learn and to bring information and knowledge to the student. Today, individuals are responsible for obtaining and shaping that knowledge for themselves.

This information age model does not supply 'navigational aids', i.e., resources for making sense of this world of choice. Nor does it supply *knowledge*. Instead, it supplies 'stuff' that individuals assemble in relation to their interests.[50] In the not-so-distant past, schools provided a curriculum that included a set of tools that had utility in relation to the problems encountered in the social and economic world. The curriculum included knowledge and skills — that is, tools for dealing with problems in a known world. Currently this curriculum has lost its utility: the world is constantly changing and because of this schools can't provide a set of topics people need to learn. [50]

Thus education is evolving from an institution in which the authority is in the teacher, to one in which the agency is in the learner, who is free to go out and collect knowledge as needed.[77] While in principle all the world may be becoming curricularized, especially due to mobile learning, the environments of learning will still vary from those where power is still exercised in traditional ways to those where the learner has power to decide. For the time being, there will be a 'mixed economy' of pedagogy and learning.

In addition, we are rapidly learning more about human learning and how people can be taught, especially from the Science of Learning discipline.[15] However, we already know a great deal about human learning that we have yet to apply as effectively as we might.[45] For example, we know that students learn in different ways and at different times and that many students respond positively to alternative styles of teaching. [85] Yet efforts to address learning challenges based on first principles have made little headway. A lack of solidarity among scholars and educators regarding many aspects of these challenges makes it difficult to achieve political agreement on how best to proceed.[45]

The Challenge of Personalizing Education

Education is currently based on a one-size-fits-all, undifferentiated approach to teaching. This simply does not work for our diverse population. Equity issues demand new approaches for people who are underrepresented in some disciplines, such as, women in science, and for others who may learn differently. Numerous studies document that no optimal pedagogy or instructional medium is effective across every learner or subject.[10. 26, 52, 80]

In some cases, women (50% percent of students) are poorly served by methods that work well with men. Gender differences in academic performance do not appear to be biological.[8] For example, basic mathematics skills can be trained and computational fluency can be enhanced with software-based interventions.[74] Currently, minorities (33% of the US population) and students with learning disabilities who require extra resources (13% percent of students in the US)[63] are not well served in our schools and are poorly reached by traditional methods. Classroom activities, such as extra time on task and peer-tutoring, that work well for students with disabilities are difficult if not impossible to sustain in classrooms without extra funding and resources. Students with disabilities often require additional staff or extra resources, something that schools are increasingly unable to provide due to budgetary constraints. These students often have complex multi-factor problems. To the extent that they are not being educated to their full potential, there is a large negative impact not only in the lives of these students but on society at large. Yet educational institutions are unable to provide potent cost-effective instruction for them. The NETP makes a strong case that increased productivity is needed to enhance education. The challenges faced by particular sub-populations, as discussed here, point to the broader difficulty of providing effective educational opportunity to all given differences in individual learning capabilities. Personalization of education is a challenge given that productivity has historically been achieved through normalization of production rather than customization.

The nature of the content and skills to be learned by students shapes the type of instruction to use, just as the developmental level of the student influences what teaching methods will work well.[26] No educational approach is universally effective. The best way to invest in learning technologies is with research agendas that include measuring the effects of the curriculum, the context, and students' and teachers' characteristics in determining which aspects of educational technology work when, for whom, and under what conditions necessary for success.[26] The technology challenge in personalizing education is to develop technology that reasons about a student as might a human tutor, observes each student's activities, evaluates her learning and finds opportunities to offer help. Technology can monitor student activities step-by-step, understand what opportunities exist for improvement (relative to stakeholder goals), and plan and execute ways to support learners to take advantage of those learning opportunities, see the Section on Intelligent Environments. Monitoring students' ability includes tracking cognitive and affective responses (perhaps using sensor readings) and interpreting (categorizing) it without judging its "correctness" but merely understanding it in terms of progress toward end states.

Students with learning disabilities can benefit from adaptive instruction — for example problem sequencing, helpful pedagogical agents and meta-cognitive scaffolding — tuned specifically to their needs. For instance, one intervention might use animated learning companions that resemble students' gender and ethnicity (e.g., Hispanic or African American) to provide advice and constructive interventions.[4] Another intervention might adjust the levels of challenge and support at key moments of students' frustration. Such computer-based interventions have a strong potential for *broad dissemination* due to their general appeal, ability to personalize tutoring and limited need for resources other than a browser.

Sensors used to recognize students' emotion and motivation.

Many personalized learning systems have been developed but most are concentrated in formal content domains (math, science, programming) and military tasks, such as, equipment operation, troubleshooting, and tactical decision making.[104] Within these domains such technology is quite successful at analyzing and responding to the accuracy of student actions. We need to move personalized systems into new domains such as art, humanities, sociology, and psychology and to have systems respond to students' affect as well as their cognition.[4,12]

The Vision for Personalizing Education in the Year 2030

We expect that by the year 2030, instructional systems will have a deep understanding of students, including their weaknesses, challenges and motivational style, including student competitiveness or need acknowledgement or attention.[88] Such systems will customize instruction and coaching to student *traits* (personality, learning style, motivation, and culture) and to student *states* (affect, level of engagement, level of frustration). A number of studies in the field of cognitive psychology have documented the benefits of different feedback techniques, for example immediate feedback vs. delayed feedback, under different circumstances.[82, 86] Educational systems will elicit student actions and provide individualized feedback. Current learning objects consist largely of passive objects (e.g., videos, slides and text). Future systems will make informed recommendations; if a student shows weakness in a skill, it will suggest remediating tools; if she shows an interest in X, and many people who like X also find Y interesting, then it will suggest Y.

Once systems can predict students' interests and abilities, we expect them to support student growth in competencies and self-efficacy. They will interact with students as do human coaches and support peer feedback. For instance, systems will ask students to make predictions about their own performance (to improve their meta-cognition) and will provide feedback and recommendations based on actual student performance. It is possible that systems will inform students about goals of which they are not aware. Systems will ultimately facilitate communities of learning. They will ensure that instruction is constructive (encouraging students to learn) rather than discouraging (telling students they are "not good" at an activity). Systems will also be self-improving, i.e., policies about when and how to provide advice will change as the system works with large numbers of students and learns which students profit from which advice.

Recommendations for Research in Personalized Education

Although there are certain well-accepted policies for personalizing activities(such as keeping students in their zone of proximal development [106] and model-scaffold-fade), many research issues remain to be addressed. For example, we recommend research to implement advanced student learning models that represent what learners know, can do, when and how knowledge was learned and what pedagogy worked best for each learner. We also recommend that research identify evidence from the learning sciences that can be brought to bear on deciding which activities to present to students. Does this research affect only the predictions? If so, how could stakeholders find out the evidence or warrants behind a prediction and impact the computational decision?

We also need a theoretical argument or empirical demonstration that personalization can occur in predictable patterns detectable by a computer, for example, through machine learning (see the section on user models). We recommend research to develop machine learning and data mining techniques, including algorithms, which are particularly adapted to educational data. How do we manage vast amounts of data, effectively store, make available and analyze data for different purposes and stakeholders? Finally we recommend that simulations and representations be developed that explain themselves to learners. How do we address communicative interaction and use multimedia to switch teaching modalities as appropriate?

Technology Related to Personalized Education

Technology can provide students with instruction that is adapted to their needs and enables them to catch up, if necessary, in private and highly supportive ways, working at their optimal pace, and thereby bringing learners lost to education back into learning.[54] It is expected that there are several low-hanging fruits (in technology) that can be exploited to achieve personalized tutors in the immediate future.[88] For example, data mining techniques are used to study the effectiveness of different types for feedback and hinting techniques for different student features (see the Section on Intelligent Environments.) This assumes that personalization needs occur in predictable patterns detectable by machine learning, which requires further research. The technology available to personalize education includes user models, intelligent environments, data mining and rich interfaces.

2. Assessing Student Learning

Assessment is critical to educational change and is one of the most time-consuming and labor-intensive parts of teaching.

The second grand challenge in education is to conduct effective *assessments*, which, for purposes of accountability and promotion, has typically meant *summative* measurement. The NETP devotes a chapter to the important challenge of assessment, ranging from consideration of what should be assessed to technology that might assist in assessment. A particular focus is on "continuous assessment," in which students can receive evaluation and feedback from multiple sources at multiple points along the course of their education.

To support learning, future education also requires the ability to conduct effective *formative* assessment. [13, 82] Assessment is critical to educational change and is one of the most time-consuming and labor-intensive parts of teaching. Because student evaluation is also highly political, the development of online tools to support teachers doing assessment is rarely addressed.[54]

The Challenge of Assessment

A compelling vision of assessment should have as its primary goal the improvement of learning.[13, 82]Assessment should be used to gather evidence that informs instructional decisions, and encourages learners to try to learn.[97, 98] This is referred to as formative assessment, or assessment *for* learning, in contrast to the traditional summative assessment or assessment *of* learning. This vision of educational assessment is exciting, powerful, and absolutely critical to supporting the kinds of learning outcomes and processes necessary for students to succeed in the 21st century.

Given the increase in so-called soft skills required of 21st century citizens, (such as, creativity, critical thinking, problem solving, communication, collaboration, information literacy, and self-direction), it is important that we develop good methods to assess these competencies in students.[88]

Furthermore, given the growing importance of lifelong learning, we need methods to measure cognitive and non-cognitive factors that are likely to be predictive of learner success. As we envision seamless and ubiquitous learning in the context of lifelong learning, this vision readily leads to seamless and ubiquitous assessment integrated with job performance support systems. *Seamless* refers to the removal of the false boundaries between learning and assessment that characterize the current "Teach / Stop / Test" model of assessment. *Ubiquitous* refers to the constant nature of assessment that feeds back results and implications into learning, anywhere and anytime.

The Vision of Assessment in the Year 2030

By the year 2030 we expect that learning environments will prepare students for lifelong learning by focusing on cognition, meta-cognition and affect. We expect that systems will measure these skills unobtrusively and help students to know whether they have improved in each area.[88] For example, we expect systems to support meta-cognition, specifically, self-regulation (the ability to control one's impulses, regardless of emotion, especially to motivate oneself to reach long term goals) and self-explanation (the ability to spontaneously explain material in terms of an underlying domain knowledge). Assessing student competencies and attributes also supports future learning and the teaching of lifelong learning skills, thus suggesting the need to develop metacognitive strategies for learning.

Research Recommendations for Assessment

We recommend research to understand the full complement of characteristics brought to bear in learning. What are learning competencies? How do they relate and how do we acquire evidence about them? We also recommend that research be funded to clarify the fusion of assessment and learning. What are new sources of assessment? How do they flow to, from and with learning, and how can we tear down conceptual and practical barriers between assessment and learning? Another research area is to ensure that assessments are useful to all parties Which stakeholders make which decisions? What information do they need, how does assessment provide evidence for those decisions, and how to best communicate the complicated results of assessment to each party?

In addition, we recommend research that explores what sources of information in students' behavior, for example, timing and pattern of help requests, can provide extra insight into the learning that is occurring. For example, recent research suggests that automatic detection of students' guessing and slipping can improve the accuracy of models of student learning.[6, 7] In addition, automatically assessing students' behavioral characteristics, for example, off-task behaviors [5, 20] and gaming the system [6, 39] in addition to learning gains [3] provides useful feedback to teachers and school administrators, helping them improve classroom management. Funding research into data mining and machine learning can exploit these extra sources of information and may provide powerful methods for improving assessment.

Technology Related to Assessment

Technology can help to assess student capacities anytime and anywhere and provide accurate information to stakeholders. It is necessary, in our shifting educational landscape, to build comprehensive models of learner competencies and attributes, and to develop assessment techniques that infer levels of those constructs. However, a great deal of research is needed to develop technologies that work with large numbers of students, see for example, the sections on user models, intelligent environments, data mining and management.

3. Supporting Social Learning

A third grand challenge in education is to support *social learning* and interactions. We can no longer accurately consider the individual as acting in isolation, especially as pertains to learning.[56, 76, 99] Social learning is pervasive and should be a component of all research that effectively addresses learning.

The Challenge of Social Learning

Recent years have seen a growth in the social networking capability of web-based services, known as 'Semantic Web' or 'Web 2.0'. These terms refer to online collaboration tools, such as photo- and video-sharing services, blogs, pod- and video-casting, weblogs, wikis and social bookmarking, that facilitate the sharing of content by users. New social arrangements find their realization in those genres. Social learning in the context of these web-based services typically involves a loose grouping of participants who share a set of common aims and practices around user-led content.[18] Social learners occupy a hybrid, user-and-producer position that can be described as being community-based on the assumption that the community as a whole, if sufficiently large and varied, can contribute more than a closed team of producers. [50] In other words, social learning characterizes a fundamental shift in agency from broadcast to content generation and a decentralization of resource provision. [50] The shift in agency is also one of user-led media content consumption, with users increasingly selecting what information to access and what music and films to watch and when.

Stability in the classroom has given way to a world of fluidity and the power of authors has given way to a world of collaborative text-making.[50] Social learning has numerous features. For example, students engaged in social learning have *fluid roles* — producers participate as appropriate to their personal skills, interests, and knowledge, and roles change as the project proceeds. Social learning revolves around *unfinished artifacts* or content artifacts in projects that are continually under development, and therefore always unfinished. Development of artifacts follows evolutionary and iterative paths. Typically the products involve *common property* and *individual merit* — contributors permit (non-commercial) community use, adaptation, and further development of their intellectual property, and are rewarded by the status capital they gain through this process.[18]

Social learning also illuminates a bifurcation of learning theories. Cognitive theories of the past have focused on the individual; learning is a computational process in which humans process information in a manner similar to that of computers (receive and store information).[2] Social theories of the past have focused on the group and suggest that social interaction plays a fundamental role in the development of cognition.[106] The theory of social interaction states that all fundamental cognitive activities take shape in a matrix of social history and from the products of socio-historical development. As members of a community, students slowly acquire skills and learn from experts; they move from being naïve to being skilled as they become more active and engaged in the community.

Now is the time to bring these two areas of learning theory together. Social learning includes the learning of individuals in communities; the learning of communities themselves as they improve their functioning and accumulate knowledge capital; and the learning of communities from each other.

The Internet can support social learning as it is about connectivity. In the beginning it was about connectivity between people. The Web swept over that and searching became about information content. Now we have come full circle and have both content and connections among people. The Internet is again becoming about connectivity.

Two effective use of technology for children outside of school are multiplayer gaming environments and social networking. Social computing is not just about chat tools, threaded discussion and direct support for interaction. It also includes designs that are used in contexts where conversations take place and that have the potential for social learning.

The Vision for Social Learning in the Year 2030

We expect that by 2030 learning communities will be distributed across space, time, and contexts, and will not be defined by dichotomies (face-to-face (FTF)/online, class/informal, etc.).[102] We expect to leverage learning in the entire experiential ecology of the child as social context of the experience and to make effective use of the entire social network of the child, including peers, parents, and outside mentors as well as teachers. Social ties will grow, interact, morph and dissolve dynamically. Mobile networks will enable individuals to spend less time in front of the computer and yet, using wireless and mobile tools, to continue to have ubiquitous computational

Mobile networks will enable individuals to spend less time in front of the computer and yet, using wireless and mobile tools, to continue to have ubiquitous computational support while traveling, visiting museums, on the bus or at home.

support while traveling, visiting museums, on the bus or at home.

We envision societal changes by 2030 that lead to learning that is no longer isolated in schools, nor the business of schools alone. [102] Learning will be highly distributed and valued by the typical citizen and will sustain value in and of the community. (For example, a team working on a biology diagnosis problem in the classroom). Then each individual student goes home and works on the problem individually. The system remembers everything done in the classroom and the student continues working uninterrupted. Students also compare their individual work with that of the team and then with that of the entire classroom. We also expect to see societal changes in the workplace. A person's career will be valued not only for what they earn, but also for how much they learn (see the Section on Beyond Traditional Boundaries).

Research Recommendations for Social Learning

We recommend research to investigate the larger *social consequences* of the move toward social learning. What are the benefits, affordances and socio-cultural impacts of digital technologies? What is their impact on notions of the self and society? [50] To what extent can these tools become a prosthesis for some users? Have they already done so?

Research is needed to explore the extent to which social learning does, can and should govern the way in which we perceive and apperceive the world around us.[50] What is the impact of the (seeming) fracturing of the self into multiple identities as well as the membership of a wide range of user groups and communities of practice? The move away from centrally determined broadcast content and media of transmission, and toward a "distributed" culture, will decrease shared cultural experience. Will that have an impact on notions of society? What of the increased fragmentation of mainstream culture into scenes and sub-cultures, each with their own practices?

Technology Related to Social Learning

We will need technology for many social learning solutions. For instance, personal spaces develop naturally and effortlessly out of online activity, for searching, persistence of object identity issues); networks of (social) agents monitor information spaces and each other for relevant information and activity. We need technology to enable learning communities to sustain, build on and share knowledge. We need knowledge organization tools to solve the meta-data problem (whether formal, folksonomy). Technology is used to support social learning in both formal and informal venues, see the sections on user models, mobile tools and networking tools.

"Science advances whenever we can take something that was not visible and is now visible. This is now taking place with respect to social networks and processes."

— Jon Kleinberg,
"The Convergence of Social and Technological Networks," 2008

---

4. Diminishing Boundaries

A fourth grand challenge in education is to re-examine the artificial boundaries established within our educational institutions: students, teachers and activities are organized into *level of education* (school, college, university and professional development), *personal ability* (special and typical students), place of study (home, work, institutions) and *type of learning* (formal and informal learning).[54] Each group has defined boundaries. One feature of mobile technology and social networks is to provide seamless and ubiquitous learning across these established boundaries. For instance, the distinction between formal (in the classroom) and informal (outside of the classroom) education may disappear as students begin to learn equally well outside and inside the classroom. Given well-managed technology, education can better match the potential unity of an individual's experience across these boundaries.

The Challenge of Diminishing Boundaries

"Many individuals do not participate in any meaningful learning at all throughout their adult lives and many others have only sporadic and highly interrupted patterns of engagement. These inequalities are highly dependent on an individual's age and stage of life, as well as patterned in terms of income, gender and social class."

— Laurillard et al., "Learning Through Life:
The Role of Technology," 2008

The current educational apparatus was created to facilitate formal learning. Learning, of course, takes place both within and outside that apparatus.

Education and learning are not synonymous, and information technology, plus other innovations, increases opportunities for learning outside as well as inside the educational apparatus. When we talk about learning, we encompass learning that occurs within the educational apparatus as well as that which does not; the impact of technology on learning might be greater outside the educational apparatus than within it. One aspect of this challenge is to examine both formal and informal education and to integrate, for example, a student's computer studies in the classroom with her searches and computer work done at home. We cannot discuss the need for formal education without acknowledging the need for custodial care of young people, even at a time when we may see less need for constrictive classrooms and daily routines.[45]

Some existing educational barriers are both technical and social in nature.[53] For example, education is beset by problems of inequalities of opportunity and outcome — with widening participation remaining a fundamental issue to be addressed by future governments. "At the basic level of ensuring equality of opportunity, platforms of access to learning will need to be low-cost, portable, durable and build upon the technologies that are already well-integrated into individuals' lives — such as mobile telephony, digital television and computer games. Similarly, modes of learning will need to follow activities which are already well-integrated into individuals' lives — such as playing and communicating."[54]

The Vision for Diminishing Boundaries In The Year 2030

Educational boundaries will be diminished in part by technology. For example, tools and resources used in formal settings will become readily available outside of the classroom (for more on technology outside the classroom see the Section on Mobile Tools) and will support the seamless transition between formal and informal environment.[19] Emerging examples of this phenomenon exist in the form of LEGO Mindstorms robotics interfaces that are used in museums, classrooms, homes, and play. Likewise, the Scratch-programming environment (http://scratch.mit.edu/) offers tools that span formal and informal environments. Further, we expect to see the line between formal and informal learning environments blurred as learners seamlessly transition between them, transferring, applying, and enhancing their knowledge, experience, and discovery and imaginative inquiry across formal and informal learning situations.

We anticipate that rich interfaces will support life long learning (longitudinal) and ubiquitous (embedded) experiences.[19] Learning will be longitudinal and lifelong as learning technologies permeate throughout life experiences. Persistent interfaces will adapt to learners across life transitions and stages. In many ways they may come to know learners better than learners know themselves. Tools will enhance and facilitate each learner's life aspirations, reflections, and engagements.

Rich educational experiences might incorporate opportunities for learners to reflect on their own learning.[19] Likewise learning scientists will have new opportunities to analyze vast new data sets, collected from the rich interfaces, that contain elements of learning, affect, motivation, social interaction, and longitudinal, indeed lifelong data and patterns of learning and engagement that will no doubt lead to new theory development with powerful impacts.

Research Recommendations for Diminishing Boundaries

> ***We recommend that funders support research to increase opportunities for learning outside as well as inside the educational apparatus.***

We recommend that funders support research to increase opportunities for learning outside as well as inside the educational apparatus. When does learning occur? How should learning be supported outside of the norm, at home and informally? We recommend that research be funded to develop tools and resources for learning that are available across society. We recommend that research support students to transfer, apply, and enhance their knowledge, experience, and discovery and imaginative inquiry across personal ability, levels of education and type of learning.

Technology Related to Diminishing Boundaries

Technology addresses boundary issues by providing easy access to educational content and learning opportunities for all of society. A further component is to have access to social contacts and collaborative networks that support the learning process. Boundary issues at many levels are addressed by technology. For example, seamless and ubiquitous learning addresses boundaries of places of study. Learners require easy access to learning opportunities and education that is both affordable and flexible in terms of time, place and pace.[54] Intelligent environments address levels of education, by allowing students to engage in learning at their appropriate level. User models and mobile tools address personalized instruction for all students and issues of seamless and ubiquitous learning.

5. Alternative Teaching Methods

A fifth grand challenge in education is to develop *alternative teaching methods*. In the past, when teachers held most of the resources and knowledge about a known world and communicated these to students, fixed teaching methods, (such as, books, lectures, drill and practice exercises, and individual exams), were sufficient for teaching students. The NETP focuses on the

concept of "connected teaching" in which teachers are connected with students and other teachers in learning communities with access to on-line resources of many kinds. It will be necessary to train new as well as existing teachers in this new way of teaching. Now that students are asked to shape their own knowledge out of their own sense of their world, new teaching methods are needed. As the world around the school has changed, old teaching methods have lost some of their utility: the earlier world to which the school could provide answers is a world with different demands.[50] For example, engaging in large scale systems thinking often means working across multiple domains, and, therefore, students need to learn, understand, and apply information that spans multiple topics. Today's students need 21st century skills, which involve creating their own knowledge in part through creativity, innovation, critical thinking and solving complex problems in new ways.[88] Schools must emphasize skills that include the ability to make informed judgments, communicate and collaborate with others, use information in innovative ways, and take charge of one's personal and civic life.

To further engage students in 21st century skills, (e.g., inquiry thinking, collaborative activities, and asking good questions), additional technology resources are needed. In addition to providing students with the ability to handle more complex, realistic problems, we need rich environments that have the potential to "develop students' communication skills and creative abilities as they become exposed to diverse cultures and viewpoints." [88]

The Challenge of Alternative Teaching Strategies Challenge

In the not-so-distant past, schools provided a curriculum that was much more than a set of things to learn, and also included tools that had utility in relation to the problems encountered in the social and economic world.[50] A fundamental change is required from teaching strategies in which authorities bring information and knowledge to students to strategies in which individuals are responsible for obtaining and shaping knowledge for themselves. We describe three such alternative teaching methods as examples of the skills students need to acquire to move into the future: *inquiry reasoning, collaboration* and *discourse and social interactions*.

Inquiry reasoning requires that students plan and manage investigations and analyze and communicate their results.[110] People need to solve messy problems without nearby authoritative help (answers supplied by instructors). Inquiry learning teaching strategies support students to generate hypotheses and provide data or evidence supporting those hypotheses. [29, 32, 100, 101] They help students work within active and authentic contexts and invite them to reflect on their own knowledge and transfer that learning into new contexts. This mode of learning is more pressing today than ever because citizens in a high-technology world need to employ scientific reasoning, to ask new questions, to generate hypotheses and to gather evidence that either supports or refutes those hypotheses.

However, teaching inquiry skills presents many challenges. Teachers need to monitor the progress of teams that progress at different rates, articulate unique hypotheses and pursue different experiments. Teachers are often concerned that the curriculum is not covered once students move off into their own investigations. Teachers don't know whether to intervene and when to encourage students to articulate questions, refine existing hypotheses, and gather evidence.[27, 84, 89] Teaching inquiry skills is time and labor intensive and often difficult to manage in larger groups.

Collaborative learning is another teaching method that is vital today as knowledge has become complex and individuals rarely solve major problems single-handedly. For example, global data needs to be processed by multidisciplinary teams in real-time 24 hours a day. Collaborative projects encourage students to articulate and reflect on knowledge, engage in active learning, and envision how knowledge is shared and extended.[28, 40] Collaboration has its own set of unique benefits; it often results in higher achievement and greater productivity; more caring, supportive, and committed relationships; and greater psychological health, social competence, and self-esteem for students.[40] Collaborative student discourse (i.e., reflective discussions among students about content) often results in learning that outperforms the ability of the best individuals in the group, produces knowledge that none of its members would have produced by themselves, and leads to the generation of new ideas.[31, 40, 93]

Yet again, teaching collaboration skills presents many classroom challenges. First students need to understand the processes by which teams of people generate, evaluate, and revise their knowledge.[42] They need to learn to listen to and work with others, and to move ahead to explore topics that may be unknown by the teacher. Resources are needed to provide supportive and flexible learning experiences and to fully engage students to work with local and distal students.

A third teaching method involves **discourse and social interactions**. Employing dialogue and socially gathering and sharing information among students is a powerful means of building individual conceptual understanding. Discourse provides an approach to constructivist learning in which students are active and engaged.[53] It enhances a teacher's role as advisor and, when successful, supports structural and institutional changes by moving classroom activities further away from teacher-centered didactic instruction and closer to student-centered collaborative inquiry.[92, 96] Social interactions support the Vygotskian[106] approach to learning based on social constructivism and the zone of proximal development (i.e., discourse with a mentor helps ensure that learning is within a student's range).

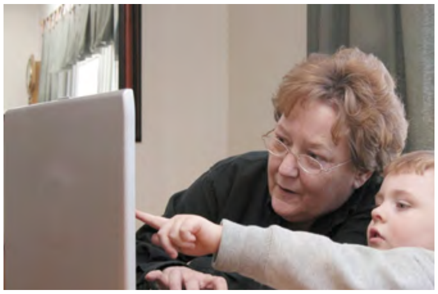
Yet, this is not a simple teaching approach and requires students to learn communication skills; how to discuss alternative approaches, engage in reflection, assess information presented by possibly distant and unseen team members, jointly collect data, explore and construct knowledge, and reach consensus. Organization and management skills are needed to share as well as to assume ownership of knowledge. Teaching such skills and knowing how and when to intervene appropriately, is time and labor intensive.[27]

The Vision For Alternative Teaching In The Year 2030

We anticipate that several new learning approaches will be supported in the future, in part as a result of new technologies.

We anticipate that several new learning approaches will be supported in the future, in part as a result of new technologies. For example, collaborative learning will be supported by software that helps match learners with other learners and/or with mentors, taking into account learner strategies and interests.[33] Software will provide coaching to students based on reviewing their work.[29] Automatic tools now mirror student participation in collaboration[44] and present just-in-time references that take into account the learner's current task context, prior knowledge and mastery and preferences. Mirror tools visualize processes, indicate components of teamwork and display how participants are contributing to team effort.[44, 94] Dimensions of the collaboration are visualized, through average participation levels, quantity of interactions, and timelines for team members. Visualizations enable students and teachers to judge how student behavior compares with the desired collaborative behavior. Through this visualization, students are encouraged to regulate their own activity and participation. Teachers will incorporate tools in their daily lesson plans. Actionable item for all team members from these tools will remove the need for constant teaching and assessment during collaboration.[110]

We expect that by 2030 tools will *advise* and coach students about their inquiry reasoning and propose remedial actions.[22] Techniques will help students create hypotheses, consider multiple hypotheses, select counterexamples and track consequences to contradiction. Such tools can now partially understand student input, monitor their activity, (e.g., data collection), gain insight into whether they are engaged in good inquiry behavior[29] and reason about the *type* of feedback to offer them.[28, 100] Current inquiry systems represent domain knowledge and track students' mastery of that knowledge. Some respond in the context of the student's reasoning and indicate whether that reasoning is consistent with the expert's reasoning. Because inquiry learning includes both learning critical inquiry skills — generating hypotheses and providing supportive evidence — and learning a topic, (such as diagnosing a patient), these tools address both sets of issues and the systems' assessment of the current student model is used to decide how to provide advice.



Another type of software that will be available in 2030 includes *metacognitive* tools dedicated to improving a person's knowledge about his or her own cognitive processes, including reflection, cognitive control and monitoring of perception, action, memory, reasoning or emotion. For example, self-regulation skills include feedback to the learners regarding their current status of learning and their ability to make adjustments about their own learning processes. New tools will detect, trace, model, support, and/or foster learners' metacognition and self-regulatory behaviors and will monitor general trends in student work, diagnose students' learning behavior and deduce or infer problems in their reasoning.[38, 94] These tools will use a variety of artifacts to infer metacognition, including physical sensors, computer models, eye-tracking, log file, physiological, think-alouds, and navigational profiles. Learners using metacognitive tools are responsible for making their decisions regarding the domain, yet the tools will help them monitor their own learning. For instance, tools will help learners monitor, regulate, control and evaluate both social and task-oriented aspects of collaboration.

We suggest that educational systems will detect students who are gaming the system...

We suggest that educational systems will detect students who are *gaming the system*, for example, using the rules of an environment against the system by clicking on hint buttons until the answer is provided.[5, 6] Such software will identify bad gaming vs. good gaming and will provide interventions even when the system does not understand students' ultimate intentions during the activity. In ill-defined domains where there are no "correct" paths, (e.g., diagnosis, art and law), software will classify the differences between a student's path and some optimal paths in terms of predicted eventual outcomes, (e.g., serious misconceptions vs. minor mistakes vs. missed opportunity for interesting sidetracks). Systems will be aware of each student's pre-requisite and follow-on activities, in addition to each student's metacognitive and affective capacities. Based on their linguistic ability, systems will understand student input (text, speech, gestures) and if they notice learning opportunities that students' cannot handle, (e.g., the student is weak on a certain pre-requisite), they will report this and suggest how to remediate students' weaknesses.

Recommendations for Research into Alternative Methods

We recommend research to support a variety of alternative teaching methods. For example, research should explore collaborative inquiry — What is the process by which teams generate, evaluate, and revise knowledge? Which tools support learning of more complex, realistic problems? Which tools match learners with other learners and/or mentors taking into account learner interests?

We also recommend projects that investigate how to best develop students' communication skills and creative abilities as they become exposed to diverse cultures and viewpoints. We recommend developing resources that support exploratory, social, and ubiquitous learning.

Technology Related to Alternative Teaching Methods

Technology currently supports alternative teaching methods. A suite of new technology tools, such as simulation and guided discovery environments[25, 108] can support both teachers and learners in inquiry-based learning. One challenge is to develop these tools so they can more easily be integrated with curricula and classroom teaching activities. Technology currently supports collaborative learning by enabling exploratory learning, social interactions, ubiquitous learning and choice and adaptivity in learning.[95, 101] Technologies that provide this support include user models, networking tools and intelligent environment.

6. Enhancing the Role of Stakeholders

... stakeholders (teachers, students, parents, administrators and employers)... will ultimately begin to trust educational technology tools and use them in daily activities.

A sixth educational grand challenge focuses on the *role of stakeholders* (teachers, students, parents, administrators and employers) who will effectively and consistently utilize technology and in some cases fully integrate technology into their activities. Education systems will consult regularly with these stakeholders, report about students' activities, emotion, meta-cognition and behavior. Stakeholders will ultimately begin to trust educational technology tools and use them in daily activities.[88]

The Challenge of Stakeholder Roles

Currently, teachers are the sole provider of lessons and learning resources for many students. What will be the role of teachers when they are invited to "collaborate" with educational systems and work as partners, with computational agents offering their best qualities? For example, teachers have empathy for and intuition about students, while instructional systems have vast memories and can infer student knowledge. The primary requirement here is that stakeholders need to trust that educational systems will fill their needs, fit within their culture and do what they are designed to do.[88] Stakeholders will need to evaluate the pedigree, intent, and authenticity of tools, trust them and know that they can evolve alongside their own needs and culture.

The Vision for Stakeholder Roles in the Year 2030

"We should also look at the future needs of the teaching professionals themselves. Teachers may not necessarily stay in the profession for life. The field may attract some professionals to move in and out for shorter periods of work in more of a 'portfolio' approach to careers."

— Laurillard et al., "Learning Through Life: The Role of Technology," 2008

We expect that teachers will take on multiples perspectives and roles. They will continue to be of primary importance in the school environment and to extend their significance to informal settings as well. Their influence will likely increase as their ability to interact with students in broader and more diverse contexts increases.[19] We see teachers participating in administrative, participatory, and pedagogic roles. As administrators, rich interfaces will provide teachers more accurate and more consistent forms of information about individuals and group learning, motivation, social activity, and opportunities, enabling teachers to respond more effectively to a greater range of student needs, given the increasingly diverse learners with which teachers interact.[19] As participants, teachers will frequently engage side-by-side with students, as members of a team and at times as followers of student leaders. In their pedagogic roles, teachers will have more tailored and higher quality information to inform their actions and a greater range of actions will be afforded them. For example, teachers working with children with special needs will have ready access and specific guidance from the latest and best strategies for their specific students, stemming from advances in educational psychology. These technologies will also empower teachers with new tools and targeted opportunities to directly apply advanced learning theories, e.g., understanding Dweck's message that the mind is like a muscle and that even though the task may be frustrating, sticking with it is a learning opportunity.

As participants, teachers will frequently engage side-by-side with students, as members of a team and at times as followers of student leaders.

Stakeholders will be confident that the systems have enforced good privacy procedures and security policies

Stakeholders will be confident that the systems have enforced good privacy procedures and security policies.[88] Stakeholders will engage technology in the educational process and exercise control over the use and evolution of systems. Stakeholders will negotiate with educational systems about the selection of instructional material or sequence of activities and will be assisted by clear interfaces that contain content relevant to individual student pedagogical goals (what students are learning and what interests they have) and will be multimodal (providing graphic, symbolic and spoken feedback, in addition to text). Stakeholders will use clear interfaces to track and analyze learners' competencies and behaviors. Decision and analytic tools support teachers to design or exchange learning activities.[54] Systems will enable stakeholders to access models of students and predictions of their learning. Stakeholders will interpret the system's current model/profile of the student, which exposes not only competencies but many other data as well.

We expect students to engage in diverse participatory roles as leaders, followers, public speakers, listeners, integrators, decision makers, supporters and contributors.[88] Particularly likely to increase is students' role as leaders; as more information technology enters the classroom students will become teachers and peers, not only solidifying and expanding their learning, but also contributing to the education of their peers and increasing their social skills and networks. We expect students to become increasingly creative, curious, and intrinsically motivated, both in formal and informal environments.[19] Increased opportunities for engaging in and supporting creativity through personal construction activities depends on using information technology to collect, relate, create, and donate.

Research Recommendations for Stakeholder Roles

We recommend research to address the historical imbalance between children and teachers — identifying those activities and environments that make teachers' experiences as engaging and motivational and productive as children's experiences. We also recommend that research extend a teacher's significance to informal settings as well as formal ones and to increase their interactions with students in broader and more diverse contexts. We recommend that research support development of more tailored and higher quality information from software so that teachers can to inform their teaching decisions. We recommend that research identify how much professional development stakeholders will need to use new systems and what kinds of user interfaces are needed.

Technology Related to Stakeholder Roles

Technology will eventually be embedded within all aspects of professional teachers' work. They will become skilled in the use and development of technology and will continue to change rapidly. Teachers and institutions will need to continue to learn how best to exploit what technology offers and to understand how learners are using it. Teachers will need specially developed learning design support tools, embodying educational requirements."[54] Today, most instructional environments focus on students in their early life stages and do not sufficiently involve teachers in the design or instruction delivery process. Rich interfaces will help remedy these limitations, by providing support for lifelong learning and a wide range of tools for teachers, including the ability to tailor the instructional content and access to student assessment records.[19] User models, networking tools and data mining tools will also be vital for enhancing the stakeholder's role in the information age.

7. Addressing Policy Changes

"Education is the civil rights issues for the 21st century... We cannot let another generation of children be deprived of their civil right to a quality education".

— Arne Duncan, Remarks at the National Press Club, 1999

The seventh and final grand challenge focuses on major and constructive changes in *education policy* that are required to address endemic educational problems.

The Challenge for Policy Changes

A *knowledge society* requires people to learn rapidly and to quickly form new learning communities. Yet the existing education infrastructure is a *perfect storm;* it fails us in multiple ways. The NETP devotes a chapter to infrastructure, focusing mainly on the technological underpinnings of networking, computational resources, and access devices, etc., but touching on the problems of technical support and available content. The concept of infrastructure embodied in this GROE report is somewhat broader, referring to the entire production system for education including not only technology and technical support, but institutional, organizational and social factors. Only 50% of the world's population receives a secondary education and in the US 30% of enrolled students do not graduate from high school.[30] Many adults do not participate in learning and others have interrupted patterns of engagement.[54] *Inequities* in education related to age, income, gender and social class are rampant.

Education should be a civil right for all people. Think of other civil rights issues: rights of women, African Americans, people with disabilities, anti-smokers. Civil rights issues take decades (often 40 years) to resolve. A useful example of a highly successful social movement that produced societal change is found in the rights of disabled people.[45] The Americans with Disabilities Act was passed in 1990, but the movement necessary to create the ADA began years earlier, and provided the momentum to enforce the ADA's implementation. The change in the past 40 years has been dramatic. This success is largely because the issue became a matter of civil rights. A somewhat more difficult struggle has been to reduce use of tobacco among American citizens. At the time of the 1964 Surgeon General's report approximately two-thirds of adult US males smoked. A sequence of scientific and health findings and corollary public policies have followed, aimed at suppression of smoking. But the social movement went far beyond such efforts, and most importantly changed the image of smoking from "cool" to "uncool," particularly by turning "second hand smoke" into a civil rights issue.[45]

If society is to embrace the scope and scale of needed changes in education, social movements must be launched and sustained over protracted periods of time.

Will a time come when the ability to think critically or do algebra are civil rights, and citizenship bears the sign over the gate of Plato's Academy, "Let no one ignorant of geometry enter"?[45] What would it take to make learning cool, and how can information technology help?

Another issue is that the educational system in the US is stratified, and people at each stratum talk mostly to people in the same stratum. Researchers at one stratum talk with each other and develop recommendations aimed at people in other strata (e.g., teachers), but there are few guarantees that those recommendations are ever internalized or that they have much effect.

Given the enormity of the educational apparatus and the degree to which it is embedded in society, it is naive to think that policy reforms as customarily understood will result in the needed changes.[45] It makes more sense to think of these systemic, broadly-based changes as social movements. If society is to embrace the scope and scale of needed changes in education, social movements must be launched and sustained over protracted periods of time.

These endemic challenges must be incorporated into any further efforts to improve education. Without incorporation, we can never reconcile a vision of a learning society with the practical challenges of implementation.[45] The nation will keep walking and will certainly end up somewhere. But we still will not know where we ought to go.

National Educational Technology Plan 2010

This Roadmap was produced contemporaneously with the production of another report, *Transforming American Education: Learning Powered by Technology, the National Educational Technology Plan 2010*, a draft of which was released by the Office of Educational Technology in the US Department of Education dated March 5, 2010. The document can be found at http://www.ed.gov/technology/NETP as of May, 2010. (**Note:** The formal bibliographic citation for the NETP can be found at the end of the References section of this report —see page 80).

The NETP, as we refer to it here, is an enthusiastic endorsement of the potential for information technology to transform education. On page 10 of the NETP report the following claim is made:

The challenging and rapidly changing demands of our global economy tell us what people need to know and who needs to learn. Advances in learning science show us how people learn. Technology makes it possible for us to act on this knowledge and understanding.

Participants in the GROE Project are sympathetic to this claim: demands for education are changing, learning sciences are revealing more about learning, and technology offers great promise for improving education. However, many years developing technologies to improve education have taught the participants that understanding learning is more difficult than it first appears, and that effective applications of technology to education is achieved more often through learning-by-doing (including trial-and-error) than by straight-forward engineering based on established first principles. One might think of the NETP as an admonition that the nation take transformation of learning through technology seriously. In contrast, the GROE Project report is a discussion of how the nation might best pursue the promise suggested in the NETP.

Research Recommendations for Policy Changes

We expect global education based on customized teaching to be effective in the year 2030. As we transfer to global (on-line) education for everyone, the cost of education will drop by orders of magnitude and many more people will be educated at a much reduced cost per person. Research is needed to determine and control *ownership of educational systems*.[104] This should be addressed to both motivate the community to collaborate and build on each other's work. Freedom of use must also be built into these systems, i.e., people should be able to choose to use or not use systems as it suits them.

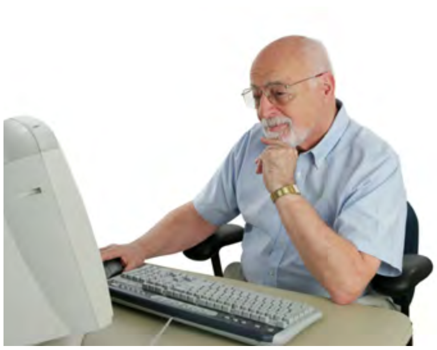
Educational communities need to be included in the design of superhighway infrastructure, social networking capabilities and systems allocations. As these systems will play a significant role in the educational well-being of the community, testing and quality assurance is a very important consideration. Research to make education a civil rights issue includes measurement of school success and failure, along with energetic out-of-the-box projects that demonstrate quantum leaps in education. For example, Early College High School takes at-risk students, eliminates high school classes and moves students into special two-year colleges. The program has a 90% graduation rate. (The Early College High School program is described at http://www.earlycolleges.org.)

Research to make education a civil rights issue includes measurement of school success and failure, along with energetic out-of-the-box projects that demonstrate quantum leaps in education.

The NETP contains a set of recommendations at the end of each chapter. Of special relevance here are the NETP recommendations regarding research and development (NETP pages 75-79). The NETP does not go into the kind of detail the GROE Project pursued in outlining research opportunities, but instead took a broad look at the research and development strategy related to education. It recommends that a "grand challenges" perspective be taken toward the needs for research and development, which the GROE Project has followed. The NETP further points to the success of the Defense Advanced Research Projects Agency (DARPA) in promoting work that builds basic understanding while addressing practical problems. It notes the authorization under the Higher Education Act (P.L. 110-315) for the establishment of the National Center for Research in Advanced Information and Digital Technologies (Digital Promise), housed in the Department of Education, designed to bring together the efforts of many different interests, including private sector companies, to achieve the promise of digital technologies in learning. It recommends a strengthened role for the Digital Promise, and suggests that such an agency could provide direction and support for an important array of research and development initiatives.

Whether a new coordinating agency is created or not, the GROE Project believes the initiatives discussed in the following pages are worth careful consideration for support by all agencies and interests seeking to improve education through technology.

Beyond Traditional Boundaries: Lifelong Learning and Health Care



The foregoing discussion suggests that education technology innovations will affect primarily traditional domains of formal and informal education, but that takes too narrow a view. It is becoming widely recognized that other major problems facing individuals in society require a fundamental shift in learning throughout the full span of one's lifetime. This section covers several aspects of lifelong learning that are becoming increasingly important both to society and to the educational community, and should therefore be included in the purview of this Roadmap.

Lifelong Learning

While some education scholars would rightly suggest that certain theories of learning apply equally to adults and young people, other scholars point to significant differences between the adult learner and the younger learner. Biological factors, such as, age-related sensory changes, a longer record of life experience (social, professional, civic, family, health, etc.), more complex psychological development, for example, capacity for transformative self-reflection, differentiation and reintegration, and assumptions of adult agency and self-direction, are among several of the distinguishing factors for learning that are more at play for mature adults. The settings where learning can formally take place, and the "reasons for learning" may be more varied for adults than for children as well, for example, professional development in the workplace.[57] For example, in the new knowledge economy, career development may be measured as much by acquisition and development of valuable and relevant knowledge across a lifetime of employment, as it is by the rank and title of each particular job.[35] In this context, "career", metaphorically, can be characterized as a repository of knowledge.[10]

The settings where learning can formally take place, and the "reasons for learning" may be more varied for adults than for children.

The following categories of adult life reflect some of the areas beyond traditional boundaries where computational technology could make a substantial contribution to adult lifelong learning.

Professional development: Skills and best practices training for job advancement; career counseling; retraining for a new vocation.

Sports and outdoor recreation: Instructional skills-based learning.

Travel: Directional way-finding; interpretive tourism (e.g. learning about heritage and cultural attractions).

Home life: Home repair and how-to knowledge.

Hobbies and avocational interests: Skills acquisition, social networking, product information, best practice.

Daily life: Driver education; learning about laws, legal issues, and civic responsibilities; news acquisition; consumer information awareness; relationship and family issues; spiritual life.

Healthcare. Medical and pharmacological information; self-care strategies; distance medicine.

Health Care

It has been known for some decades that lifestyle choices have a dramatic impact on long-term health. Campaigns to reduce the incidence of smoking provide evidence that the message is understood at the policy level, and when mitigation efforts are implemented aggressively, behavioral changes follow and desired health effects are achieved. The recent surge in obesity offers another instance where behavioral modification might be needed to curb a looming public health disaster.

The rise of Internet-based communication, especially use of the World Wide Web, has enabled a dramatic change in the flow of information between researchers, health care providers, patients and the population at large. This was first noticed in the shift in information asymmetry between health care providers and patients, as patients gained access to information about their conditions that previously was available only to providers. This, in turn, has changed the relationship between providers and patients.

It is now possible to enlist patients in their own health care decisions and treatments more effectively than before.

It is now possible to enlist patients in their own health care decisions and treatments more effectively than before. Patients suffering from particular conditions can join in chat groups or other forms of on-line discussion to compare notes and learn from each other. These changes suggest that the technologies discussed above could improve learning about health dramatically, with possibly revolutionary consequences for the nation's health care system. Health care is but one of many applications of information technology that go beyond traditional educational boundaries.

B. Education Technology Recommendations

A major goal of the GROE project is to identify promising technologies... to satisfy some of the educational challenges described in the previous section.

A major goal of the GROE project is to identify promising technologies, with associated practices and communities that can sustain those practices, to satisfy some of the educational challenges described in the previous section. Furthermore, each of the educational grand challenges will likely require a blend of several technologies. This section identifies opportunities to engage technology to meet some of these educational needs. We selected seven technologies that show great promise for educational innovation and reform and describe these technologies along with a 20-year vision for each and a research agenda to help realize the vision.

Before we describe these technologies, we note that the technology vision for 2030 moves beyond the realm of currently available hardware and software. Admittedly, many of the technologies in the vision already exist in some form and many have features now being tested in classrooms. Yet current systems have not been combined on a large scale or in optimal ways for education; they often provide fixes or add-ons to education. We do not provide a comprehensive review of the many ways that technology has already been integrated into current education; such reviews exist in other documents.[110]

One challenge for educational technology is to move it beyond the realm of isolated projects in which each research group uses idiosyncratic conceptual frameworks and methods.[26] Instead, for this field to make progress, researchers need to adopt common research strategies and models, and as a community undertake collective scholarship that subdivides the task of understanding the strengths and limitations of education technology.

The emerging forms of technology described in this section will challenge, if not threaten, existing educational practices by suggesting new ways to learn or offering new support for students.[59] The vision described below requires substantial further research and development. Numerous agencies provide opportunities for funding, including, in the United States, the National Science Foundation, National Institutes of Health, and US Department of Education.

The research agendas suggested by this report provide one possible way to adopt such common research strategies. The selected technologies are not exhaustive and many others might have been considered, e.g., cloud computing, robotics and computer graphics. We selected these technologies as they are already being pressed into service, including *user modeling, mobile tools, networking tools, serious games, intelligent environments*, *educational data mining,* and *rich interfaces.*

1. User Modeling

The first information technology that shows great promise for education is *user modeling* or software that identifies and represents student competencies and learning achievements. Modeling for students may involve techniques that represent content skills, such as mathematics and art history; knowledge about learning, for example, metacognitive knowledge, awareness of "how to learn"; and affective characteristics, such as emotional states.

User modeling aims to make information systems user-friendly by adapting the behavior of the system to the needs of the individual...

Modeling is used for assessment of learning, by measuring changes in the student in any or all three of these areas.[88] User models represent *inferences* about users, including their level of knowledge, misconceptions, goals, plans, preferences, beliefs, relevant *characteristics* of users (stereotypes); and users' records, particularly past interactions with the system.

In consumer-based software, (e.g., shopping or news sites), user modeling provides recommendations to users for future purchases based on stereotypes, classifications or past buying behavior. User modeling aims to make information systems user-friendly by adapting the behavior of the system to the needs of the individual and has already been applied in information retrieval, filtering and extraction systems and adaptive user interfaces.[67] Personalization of content for users is practically certain to benefit education. Thus generic tools that allow for the easy development and maintenance of personalized systems will be equally necessary for education in the years to come.[48]

The Vision for User Modeling

Predictions concerning the future of software are speculative at best, due to the rapidly changing nature of software, languages, networks and hardware. We clearly do NOT know the future, nor will we specify any solutions up front! We specify areas that need work, and some promising directions for work. These are socio-technical solutions, recognizing the need for solutions that have large social components. However, in this and similar sections, we venture forth and list considerations about likely future capabilities of seven targeted technologies.

We envision that by 2030 user models for students will be complex, not only representing what students *know, do* and have *abilities* for, but other factors too. For instance, user models will track when and how skills were

learned and what pedagogies worked best for each learner.[16] Moreover, user models will include information on the cultural preferences of learners, their personal interests, learning goals, and personal characteristics, to select the optimal mix of learning environments, pedagogy, visualizations, and contexts that maximize engagement, motivation and learning outcomes for each individual. When the learner is part of a group, the model will make the best compromise among the individuals who are part of the group.

Most likely, by 2030 *user model servers* will be readily available for education. Servers are similar to generic user models in that they are separate from the application and will not run as part of it.[48] User modeling servers will be part of local area networks or wide area networks and serve more than one application instance at a time.

We also envision that by 2030 user models will support assessment for both *formative* issues (the degree to which the student has learned how to learn — for the purposes of improving learning capacity and effectiveness) and *summative* considerations (what is learned — for purposes of accountability and promotion). In this regard, we need approaches to user modeling that lead to valid and reliable inferences about student learning that are both diagnostic and predictive. Such a perspective concurs with the view that assessment should be dynamic over time.

We expect that by 2030 *privacy* issues in educational user models will be adequately addressed. Student privacy concerns and national and international privacy legislation have a considerable impact on what education applications may do. Strict privacy enhancing software tools and Internet services will exist. Generic user modeling systems will facilitate compliance with such regulations, as well as support privacy-enhancing services.

We expect that by 2030 privacy issues in educational user models will be adequately addressed.

Current user modeling techniques are handled by each individual educational system. Furthermore the construction cost of such models is about one year's time for a graduate student. For example, to measure a specific construct, (such as algebra skills), persistence, help-seeking behavior requires a substantial amount of effort to construct relevant conceptual and statistical models.[88] Thus, the current approach does not scale to the increasing numbers of electronic learning environments that should have user models. Consequently, we envision that by 2030 user models for education will be developed as *shells* that exist independent of the instructional software and attached to the software only after it has been activated.[48] Instead of building a user model for each software application, generic models will define

their basic functionality and then be further constructed during development time. The term "shell" is borrowed from the field of expert systems and describes environments containing the basic components of expert systems.[64] Associated with each shell is a prescribed method for building applications by configuring and instantiating these components. Shells support construction of knowledge bases through use of inference engines. Generic user models will serve as separate components and usually include a representation system for expressing the domain knowledge, (e.g., logic formalism, rules, or simple attribute-value pairs), and a reasoning mechanism for deriving assumptions about users from existing models.

It is likely that *machine learning* (ML) techniques will augment user models automatically. ML refers to a system's ability to acquire and integrate new knowledge through observations of users and to improve and extend itself by *learning* rather than by being *programmed with knowledge*.[78] These techniques organize existing knowledge and acquire new knowledge by intelligently recording and reasoning about data. Thus, observations of students' past behavior will provide training examples that will form a model designed to predict future actions.[107] These techniques have been used to acquire models of individual students interacting with educational software and group them into communities or stereotypes with common interests. ML techniques are promising in cases where very large sets of usage data are available, like educational software on the Web.[48] These techniques improve teaching by repeatedly observing how students react and generalizing rules about the domain or student. These paradigms enable tutors to adapt to new environments, use past experience to inform present decisions, and infer or deduce new knowledge. Intelligent environments use ML techniques to acquire new knowledge about students and to predict their affect and their learning.[3, 39]

... observations of students' past behavior will provide training examples that will form a model designed to predict future actions.

By 2030 user models will probably be able to *adapt to new student populations*. Students have a variety of learning needs. For example, exceptional students learn beyond their age group, and special needs students require accommodations. Yet educational software is often built for the average student, not for advanced students or slow learners. ML techniques can enable software to acquire knowledge about distinct groups and add that to their original code. Techniques can make decisions based on experience with prior populations and enable software to reason "outside" the original variables that made up the system.

Research Agenda for User Modeling

We recommend research on *generic user models*, i.e., user information maintained in repositories that are available to more than one application at a time. Research should explore how to perform reasoning about users and identify how to develop *expressiveness* and *strong inferential capabilities* by using first-order predicate logic, reasoning with uncertainty, plausible reasoning when full information is not available, and performing conflict resolution when contradictory assumptions are detected.[48] Research should explore user modeling shells that support complex assumptions and complex reasoning about users to facilitate widely used and highly flexible models that will evolve to a global standard.[48]

Research should explore user modeling shells that support complex assumptions and complex reasoning about users to facilitate widely used and highly flexible models that will evolve to a global standard.

We also recommend that research identify features of *user model servers*. For example, should they be "centralized" (reside on a single platform only) or distributed across several platforms to increase their performance and availability? Decentralization helps increase the performance and failure tolerance of user modeling servers and their ability to integrate into existing environments.[48] Most commercial servers allow the virtual integration of heterogeneous "outside" resources of user information.

We support research into user model *security, identification, authentication, access, control and encryption*.[48] "Subclasses" of generic user modeling systems have already evolved, most prominently for student-adaptive tutoring systems that impose very specific requirements on generic student modeling system, which are expected to be usable within different subject matters.

Research is needed to study how machine learning (ML) techniques can achieve *increased software flexibility* and *reduced cost.* ML techniques should be researched to enable user models to *adapt to new student populations* and to counter the typical inflexibility of educational systems that fossilize and require human intervention to be extended, in terms of either domain or type of user.[91] Clearly inflexible instructional software is let loose in a constantly changing environment, (e.g., the Web), under conditions that cannot be predicted.[105] This method is limited and shortsighted for many reasons. The original author had incomplete knowledge about the domain as well as student and teaching strategies, and thus portions of the system remain forever incomplete. This lack of flexibility is a contributing cause of the high development cost and effort to construct tutors. Flexibility and cost are two sides of the same coin. If these environments were more flexible and able to accommodate themselves to new students and new topics more easily, the per-student training cost would be reduced. Currently many person-years are needed to construct a single environment; for example, a detailed cognitive task analysis might take months.

We recommend research into *reasoning about uncertainty* for educational software. Most educational software represents student knowledge using formal logic, (e.g., student A knows skill X). However, this representation does not include the fact that authors cannot know with certainty how to represent a skill or whether students actually learned this skill. Knowledge in educational software is incomplete in terms of its user model and therefore reasoning under uncertainty is needed. ML techniques use approximations and reach weaker conclusions than do traditional tutors, e.g., "This student will succeed on the next problem with a probability of n%." ML offers a varied and rapidly expanding collection of tools that provide educational software with a potentially significant amount of new knowledge and predictive power. Representing and reasoning about students, domains, and teaching knowledge involve complex and difficult processes. ML both makes this process more complex and provides an opportunity to solve more interesting problems.

2. Mobile tools

The second information technology that we describe includes *mobile tools* or wireless devices that provide remote access to information and enable social interactions to take place anytime and anywhere. The intrinsic nature of mobile tools is to offer *digitally facilitated site-specific learning* that is motivating in part because of the degree of available student *ownership* and *control* (over goals).[54, 43, 79] '*Learning-in-context*' and '*continuity between contexts*' are aspects of learner ownership and control that explain why mobile tools make learning easier and more effective. Mobile learning is important because it results in student access, personalization and engagement.[53] Features like communication with peers contribute to suggest why mobile learning might be 'fun.'

In mobile learning, individuals who have smart mobile devices beyond simple phones, (e.g., iPhones), are accustomed to immediate access to the world via the Internet, and to the notion that all the world should be ubiquitously available.[50] *Ubiquitous* access to resources for learning assumes an attitude towards the world in which everything is always curricularized, everywhere. Some scholars suggest that everyone who inhabits the new perspective is mobile and for them "All the world is mobile."[50] This perspective in which the world is seen as a curriculum becomes shaped by that experience and expectation. That person is always expecting and ready to learn. This perspective has left the individual constantly mobile — which does not refer to a physical mobility but to a constant expectancy, a state of *contingency*, of *incompletion*, of moving toward completion, of waiting to be met and 'made full'.[50]

A key point about mobile tools is that they are *not* defined in terms of artifacts that students take to new locations.[50] Rather, the perspective is that what is 'mobile' are the individuals themselves or their characteristics and not the artifact or information. The key point is that students are now able to bring into conjunction things that might previously have been relatively difficult to join. An instance of this might be data-logging. Students take devices with them, whether to a field or a meadow, thereby transforming the devices into science classrooms. When students leave the school to go to the meadow or when they return, they, have in fact not left a site of learning: they have turned the new environment (meadow) into *a site of learning*.[50] Said another way, in mobile learning the digital representation of physical objects is in the same location as the learner.[70] Definitions of mobile learning often capture more than the simple notion of movement; they often include flexibility, social relations, constructivism, and varying contexts, which are shared with many other learning technologies.

Students take devices with them, whether to a field or a meadow, thereby transforming the devices into science classrooms.

The Vision for Mobile Tools

We envision that by 2030 mobile technology will provide a wealth of tools for learners. Ubiquitous access will enable students to be in a seamless learning mode *wherever* they are, whether stationary or moving, *whenever* they wish, synchronously and asynchronously, *whatever* their environment (formal and informal settings), with *whomever* might be appropriate, (known and unknown participants), and for *whatever tools* they need, including search engines, documents, data and analysis, independent of place, levels of education and personal ability.

We expect that by 2030 mobile tools will support a variety of student activities: *exploring* (real physical environments linked to digital guides); *investigating* (real physical environments linked to digital guides); *discussing* (with peers, audio or text); *recording* data (sounds, images, videos, text, locations); *building, making, and modeling* (using captured data and digital tools); *sharing* (captured data); *testing* (the products built, against others' products, comments, or real physical environments); and *adapting* (products developed).[53]

In mobile learning the object of study adapts to the context in which it is placed, i.e., variables in regional and network space are fixed in fluid space.[53] The emphasis is often on the nature of the physical environment in which the learner is placed. Another promising aspect is that *motivation* will become a focus for what mobile learning offers. It is clear that learners

working with mobile learning enjoy the process in a different way than, say, those working with interactive gaming technologies.

Research Agenda for Mobile Tools

We recommend that funders support research that focuses on the meaning of *mobile learning*. Although mobile digital technologies hold great promise for unlimited access to educational commodities and for the consumer-learner's sovereignty of choice, many research issues remain to be addressed.[50] — Who is mobile? What is mobile? Whose agenda is at work, with what power, with what principles of recognition of learning?

We recommend support for research that focuses on how the mobile *agenda* is presented and whether it is accepted or recognized by potential learners. As learning escapes the frames of brick school houses— a matter in which the e-technologies are deeply implicated — these are questions of increasing importance.[50] We might also ask about the effect on individuals of a curricularized world, a world seen in terms of occasions and resources for learning.[50] Where are the sites of difference, from where entirely different perspectives open up? Where are the opportunities for (seeming) downtime? And where are the times for reflection? In the world of insistently urgent choice in a pedagogic market, where is the time to opt out? In a period of increasing speed where is the time for slowness?[50] We definitely need to ask whether the task for us is that of adaptation of ourselves to technologies (including the social technologies) or whether the urgent task is a careful consideration of the utility in a wide range of ways of our adoption of technologies for considered purposes?

We recommend funding to support research that identifies pedagogical challenges relevant to mobile learning.

We recommend funding to support research that identifies *pedagogical challenges* relevant to mobile learning. The point of turning to new technologies is to find the pedagogies that promote higher quality learning of a more durable kind than traditional methods.[53] We need to understand what it takes to learn and then develop the pedagogical forms that are most likely to elicit the cognitive activities learners need. Using this analysis we would then be able to evaluate the best characteristics of mobile tools for learning.

We also recommend that funders support research into the *physicality* of wireless devices. Due to their small size, the amount of data that can be displayed at any one time is limited as is the ease with which they can be manipulated.[50]

We recommend research into the *teacher's role* when using mobile tools. How do we characterize and represent the different forms of the teacher's constructed environment that best support learning?[53] Mobile learning, being the digital support of adaptive, investigative, communicative, collaborative, and productive learning activities in remote locations, proposes a wide variety of environments in which teachers can operate.[53]

A danger exists that the educational community may fail to keep pace with the developments in the life worlds of young people.

We recommend that funders support research to *manage* mobile tools. As learners move between multiple environments — school, college, workplace, home, etc —information technology management across the related sectors is required on a massive scale.[54] The challenge is to make this problem easier — for the technology to help manage the integration and interoperability that is too complex for individual educational administrators to handle. There is a social component to this management issue. A danger exists that the educational community may fail to keep pace with the developments in the life worlds of young people. There is a potential disconnection between the way young people operate in their daily lives and the way educational institutions interact with them in a 'mobile society in flux', in quantitative and qualitative terms.[50]

3. Networking Tools

The third technology that holds great promise for education involves networking tools, which are particularly powerful for social learning. In recent years, we have seen a growth of web-based services that enhance the capabilities of social networking. Often referred to as Web 2.0, these technologies include tools, (e.g., Facebook, YouTube, pod- and video-casting, weblogs, wikis), that facilitate the sharing of content by users. Such tools result in a general decentralization of resource provision and reflect a fundamental shift in *agency,* from teachers who broadcast information, to students who generate content. This shift is also propelled by user-led media content consumption, with users increasingly selecting what information to access and what music and films to watch and when. This has given rise to a loose grouping of participants who share a set of common aims and practices around user-led content creation communities.[18]

"A world of stability has given way to a world of fluidity; a world of the power of the author has given way to a world of collaborative text-making; and a world of canonicity — whether of knowledge or of text — has given way to a world of provisionality."

— Gunther Kress and Norbert Pachler,
"Thinking about the 'm' in m-learning," 2007

The Vision for Networking Tools

We envision that in 2030 networking tools will become more *valued* and more *fairly represented* in educational practice. Engagement in the information society often requires real-time responses over lengthy time periods; modern problems are not typically solved by single individuals over a finite length of time. We envision that by 2030 network tools will facilitate individuals to learn *within* communities, communities to *construct* knowledge, and communities to learn from one another. School students clearly do not construct original knowledge in the same way as do research communities, but they can learn from community-based project work.[40]

By 2030, teachers will become knowledgeable facilitators of communities of learners.

By 2030, *teachers* will become *knowledgeable facilitators* of communities of learners.[56] Moreover, teachers themselves will use new technologies to become members of teacher communities of practice and inquiry and we see this as essential to their transformation from transmitters of knowledge to facilitators of learning. In this new social space, students occupy a hybrid, user-and-producer position that can be described as that of community-based product that proceeds from the assumption that the community as a whole, if sufficiently large and varied, can contribute more than can a closed team of producers, however qualified they may be.[50]

We envision that network tools will be *pervasive* and a component of all research that effectively addresses learning. Active students learn continuously in settings where they are interacting and working with others. Students will take on *fluid roles* — producers participating in a way that is appropriate to their personal skills, interests, and knowledge. This changes as a project proceeds. Students will work with *unfinished artifacts*; content artifacts in projects will be continually under development, and therefore always unfinished.[50]

Another vision for 2030 is that socio-cultural developments will lead to the decline of meaningful differentiation between learning *inside* and *outside* formal educational settings. The augmentation of intelligence through technology can best be understood as the most recent stage of externalisation and objectification of experiences and insights as well as an enhancement of our capacities for developing conceptual worlds. Ubiquitous, and context-aware technologies result in a shift 'from smart planning to smart situated actions.'[31]

We expect that by 2030 we will understand the mechanisms that explain the power of social learning, including the role of peer pressure and knowledgeable others.[56] Consequently, we can take the desirability of certain forms of social learning as a given. Moreover, non-social forms of learning, e.g., students working alone through textbooks, are over-represented in current education systems.[56] Within education, specific forms of social interactions, often called "dialogic," have been robustly demonstrated to be effective for engaging students in higher-order thinking and the development of "soft skills." [41, 60, 95]

... new students initially learn from knowledgeable others; in turn they go on to become the knowledgeable others to new students.

We suggest that in 2030 two views of social learning that are implicit in education literature will emerge. [56] These views are not obviously compatible. The term "*personalization,*" in which individuals are viewed as rational agents who can and should make decisions for themselves, remains popular with researchers and policy makers and carries shades of "mass customization" and "consumer choice." Conversely, the second view of social learning, in which students learn best when accompanied by others who help to challenge them, appeals to Vygotsky[106] and social-culturalism, which are equally popular and carry shades of *collectivism* and *enculturation*. Often in a given educational technology document both these perspectives are implicit, unchallenged and in apparent contradiction. Luckin et al.[50] argue that these perspectives must be explicitly admitted and harmonized. One view is that new students initially learn from knowledgeable others; in turn they go on to become the knowledgeable others to new students. Our view is of the student in the role of both *apprentice* and *expert.*

By 2030 we will also better understand how social learning impacts student *motivation* in learning and have evidence about whether or not increased motivation impacts learning.[56]

Research Agenda for Networking Tools

We recommend that funders support research to identify if and how networking tools *motivate* learning. What evidence about networking supports its impact on student engagement and learning? What are the *factors* involved in motivating students, such as the pressure to perform that comes from peer review and team commitment? What is the impact of a person's sense of duty to community? Researchers have explored different methods of making motivation explicit and promoting motivation through tools that acknowledge social status changes and reward students for participating in positive ways (being a helper/finding the right helpers).[53] More research is needed to see if explicit rewards create more motivation in social learning environments. Does motivation in social environments lead to improved learning (deeper knowledge, better transfer, quicker uptake, etc.)? Research is needed to decide how much effort to expend on building systems that motivate students.

Research is needed to identify how to sustain social learning in ways that are highly *distributed* (across distances) and *collaborative* (working together).[100]— How do we develop integrations and blends of devices and platforms that more effectively support distributed/social learning? How can we discover innovative ways to untie computing resources from the desktop or laptop and make possible the persistence of individual activity that leads to value for others asynchronously and helps students to re-factor virtual "space" to be defined by task or topic.[100]

We recommend that research both mediate social interaction in the community, and also observe the community. For the former we need to explore student *interactions distributed across* space, time and media, and with data in a variety of formats.[102] How do we support learning communities to flourish without requiring that participants or educators have technology skills? Which Internet objects are available for shared social learning or are objects of conversation, for example, a shared graph, beyond current ones that enable researchers to see social interactions, for example, data mining, visualization tools, virtual "field" research tools. To research the latter, or observe the community as researchers, we need to identify which representational advances and shared instruments, in which representations mediate the daily work of scientific discourse, enable researchers to better see students at work in social communities.[102]

We recommend that research to explore student interactions distributed across space, time and media, and with data in a variety of formats.

We recommend that research to explore student *interactions distributed across* space, time and media, and with data in a variety of formats.[91] How do we support learning communities to flourish without requiring that participants or educators have technology skills? What Internet objects are available for shared social learning or are objects of conversation, (e.g., a shared graph), beyond current ones that enable researchers to see social interactions, (including data mining, visualization and virtual "field" research)? What representational advances and shared instruments, in which representations mediate the daily work of scientific discourse, enable researchers to better see students at work in social communities?

Research is needed to develop new and possibly more appropriate definitions of *far transfer,* which is often stated as the real goal of learning.[56] How can we show that what happens in social learning environments and games is (or is not) a close match to what happens in the real world and therefore leads to more opportunities for far transfer? How can we use a combination of cognitive research instruments and real world data (interaction patterns, ethnographic data) inside and outside social learning environments to inform the debate about the concept of transfer? Such research will address a well-recognized concern and need to use what is learnt to operate in the real world.

We recommend support of research to identify new methods and contexts for *assessment* of social learning environments and games.[56] How is participation, (e.g., on bulletin board posts) providing help to others, seeking help, valued? Is learning and rate of growth a result of deep and meaningful contributions to the community? Is the potential for re-enactment a demonstration of deep knowledge? How important are group interactions, management, planning, leadership, peer reviews, and role modeling to learning? Such research will enable us to finally move beyond the individual testing of shallow, factual and procedural knowledge (i.e., the current standardized test paradigm) and on to the assessment of important 21st century skills, such as creative problem solving, critical thinking, collaboration, and persistence.

We recommend that research be supported to influence learning in *socio-technical* systems by design.[102] The term "socio-technical" is used in recognition of the very large impact of social constructs in education. We would be naïve to think that technology alone is a solution to education. The failure of technological determinism is well documented.[47, 34] Yet we can seek technology solutions that fill in the gap between detailed qualitative case accounts (providing insight into situated accomplishments) and quantitative methods (finding patterns in aggregate data) that risk distancing researchers from the interactional processes by which participants appropriated the technology.[102]

We recommend research to investigate the relationship between individual learning and social learning through tracking interactions over time inside and outside social environments and games.

Large-level *social consequences* exist for educational software based on social networking. We recommend research to investigate the relationship between *individual learning* and *social learning* through tracking interactions over time inside and outside social environments and games. When is the time for isolated skill practice (e.g. "time for thinking") and when is the time for team interaction (e.g. "time for working with others")? Such research will offer evidence to hone individual instincts, supporting continued engagement with learning and promoting effective lifelong learning.

We recommend funding to identify what it means to be an *individual* in a *technology-mediated learning community*. For example, such research will identify the roles taken on by students to seek or give help, lead, scaffold, help helpers, or to recognize the skills and value of others.[56] When is it appropriate to conform and when to break new ground? How can we make learning with and from a community more efficient, promote the development of 'soft' skills and resolve the tension between personalization and community?

We support research to identify what it means to be a *productive technology-mediated learning community*. Such research will offer evidence of how to make the learning within a community more efficient, explicit, teachable and re-usable. How do we *represent knowledge*: including emergent knowledge and accumulated knowledge?[56] How can we design complex systems that support multiple complex goals, activities and members, any or all of which may be in conflict?

Networking tools and their affordances have a significant socio-cultural impact that researchers should address. To what extent can technology become a prosthesis for some users? Has it already done so? What is the impact of these tools on *notions of the self* and *society*?

4. Serious Games

"Will children gain from instant access to intelligent tutors, multimedia online encyclopedia and global communities or will they play ever more realistic war games?"

— Russell and Norvig, *Artificial Intelligence: A Modern Approach*, 2002

Research has shown that *fun* does play a pedagogical role in learning and is a characteristic of successful learning processes.[24] Research has also shown the potential of digital games to facilitate the 'flow' associated with learning. *Serious games* have an explicit and carefully thought-out educational purpose and are not played primarily for amusement. They involve mental contests played by users with computers in accordance with specific rules that use entertainment to further specific objectives, e.g., training, education, health, public policy, and strategic communication.[111]

Although there is no shortage of voices promoting the promise of *games* for *learning*, a number of recent reviews on the efficacy of educational games for learning report mixed and fragmented results. Two frequently made claims are that games are inherently more *motivating* than traditional computer-based learning environments and that skills exercised in modern massively-multi player on-line games (MMOGs) *transfer* to the real-world. These skills typically include non-traditional skills, such as leadership, negotiation, and communication.[15] Although the arguments are compelling and intuitive, there is to date little evidence to support such claims.[56] It is also often claimed that modern games engender a sense of presence, or "being there," but little empirical work has been done that connects presence to learning.

The Vision for Serious Games

We envision educational games that will provide new directions for learning science researchers to explore.[56] We expect that research will enable practitioners to make more informed decisions about when immersive environments are appropriate, when they may hinder learning, and what kind of realism is necessary for learning.

Researchers will be able to evaluate the impact of games on learning, "soft skills" and motivation.

We also predict a largely empirical future for educational games.[56] Researchers will be able to evaluate the impact of games on learning, "soft skills" and motivation. On the other hand, large numbers of educational games have been developed in the commercial sector and from research labs with limited or no evaluations. Commercial (non-educational) games drive many of the advances in graphics and sound. Other areas of AI research contribute to better educational games, such as intelligent techniques for stealth assessment (cognitive modeling),[83] guidance (intelligent environments) and identification of productive and non-productive learner behaviors (educational data mining), to name a few.

We envision that by 2030 it will be possible to instrument the real world, with instruments such as sensors or cameras that detect student emotion, in ways similar to how computer-based learning environments are instrumented and this will increase our chances to detect far transfer.[56] An example of this includes automated conversational and possibly physiological tracking (e.g., to detect good listening skills and non-verbal behaviors for leaders). These questions should be considered within a broader understanding of immersion that go beyond just video games — for example, emotionally charged and compelling movies or books may be just as effective at generating levels of immersion that increase presence, sustain motivation, improve memory encoding skills, and another example is that we remember better with emotional engagement, and promote far transfer.[56] It may be that tools exist in other communities (such as psychology) that may enable more accurate determination of far transfer. Again, these are empirical questions we believe are answerable within 20 years.

Research Agenda for Serious Games

We recommend that funders support research to determine whether games are inherently *more motivating* than traditional computer-based learning environments.[56] How do pure entertainment games manage to create such deep intrinsic motivation that hooks users for such a long time and with such passion? What is motivating about games? What makes people spend so much time in games to improve their skills level? Could work with games reduce the 10,000 hours needed to gain expertise or mastery in a new domain? Such research will increase our understanding of why gamers voluntarily engage in drills and how we can harness this underlying force for learning.[56] It could also lead to efficiency gains and ironically help learners appreciate the value of hard work. Can we apply this understanding of motivation to educational serious games?

We recommend research to identify the underlying properties of games that support deep conceptual knowledge.

We recommend research to identify the *underlying properties* of games that support deep *conceptual knowledge*.[56] — What is the relationship between deep conceptual knowledge and soft-skills; between deep conceptual knowledge and higher-order thinking skills; deep conceptual knowledge and ill-structured problems? Such research will enable us to identify the benefits that serious games might really offer. Does increased motivation lead to improved learning (deeper knowledge, better transfer, quicker uptake, etc.)? Do skills exercised in large on-line games *transfer* to the real world? How much effort should we expend on building systems that motivate students?

We also recommend research to explore non-traditional skills, (such as leadership, negotiation, and communication, in games). Are these skills developed in online games and do games engender a sense of *presence*, or "being there," and what is the degree to which presence is linked to learning?

We recommend that funding agencies support research to develop scientific understanding of the relationship between *immersion* and *learning*.[56] What is the scientific understanding of the factors that contribute to feelings of immersion and presence, such as *realism, engagement, narrative content, sincere involvement*?[56] Such research will offer evidence to support current assertions about serious games that are not grounded in hard science; that is, that we believe to be true, but have not yet documented.

We recommend funding to *conduct a meta-analysis* across all examples and conclusions from practitioners in the areas of games and social learning. This may identify properties that can be applied to learning more generally and will save us from re-inventing the wheel.

We recommend that funders support research to identify how teachers might *integrate games* and *simulations* with more conventional forms of classroom instruction.[26] What are the constraints and opportunities that exist for games along with opportunities for deep individual learning afforded by the classroom environment? What are the opportunities for psychosocial learning and motivation provided by classroom activities?

5. Intelligent Environments

The fifth technology that holds great promise for education involves *intelligent environments,* or software that integrates artificial intelligence techniques, including modeling, natural language processing, machine learning, into educational software to provide knowledge about the domain, student and teaching strategies.[110] Intelligent environments provide flexible and adaptive feedback to students, thus enabling content to be customized to fit personal needs and abilities and augmenting a teacher's ability to respond. Such systems move beyond teaching a single task and will be *domain independent*.[16] They will teach "soft" skills, such as creativity, critical thinking, communication, collaboration, information literacy, and self-direction, and will be open-ended and exploratory in nature, allowing learners to question and enhance their understanding about areas of knowledge in which they are motivated to learn.

The Vision for Intelligent Environments

We envision that by 2030 intelligent environments will integrate agents that act as *'facilitators'* according to the needs and preferences of learners.[104] These agents will request particular topics and knowledge components on behalf of students and may interact with each other. They will provide a complete learner model; e.g., orchestrate their own interactions, allowing certain (evaluated and approved) active objects to place themselves in context and expect them to self-assemble and adapt to the learner's characteristics (cognitive, conative, previous skills, culture) and their needs (disabilities, learning difficulties).

We anticipate that intelligent environments will *be self-learning*.[16] Agents and active objects will integrate machine learning techniques (see discussion in the Section on User Modeling) that learn about students and classify teaching strategies to work with individual students. These environments will improve their performance based on evaluating their own usage and student learning outcomes from thousands of previous students.

Future intelligent learning environments will probably allow learners to move *seamlessly between real and virtual worlds*.[16] *Virtual worlds* will present environments *beyond the classroom* walls, (e.g., a trip to the Egyptian pyramids); for things *too small to see*, (e.g., molecular level transformations); *too large to include in the real environment*, (e.g., a model of Mars and its moons); *too long in time,* (e.g.,the erosion by a river); or *too quick to see*, (e.g., the beating of a hummingbird's wings).[16] For example, in learning science, a chemistry student might work in the classroom with real lab glassware, chemicals and equipment, but then move into a virtual environment to rapidly repeat the same experiment with different chemicals or to automatically collect data. With little effort on the part of learners, environments will take current reality as a starting point for a virtual engagement. The software will recognize the current situation, provide learners with tools that are automatically assembled given the specific situation and learner's needs and learning goals, recreate this world in the virtual context, and provide access to knowledge.

Environments might augment the real world equipment...

Environments might *augment* the real world equipment with instruments such as embedded sensors in the lab glassware that know how much of a liquid a student has added, detect that it has been placed on a Bunsen burner, monitor the rising temperature and display the resulting graph.[16] The *simulation* part of the environment will represent the chemical interactions at the molecular level while the *virtual* part will represent other team members in a group-based learning task. Intelligent environments will be aware of each student's prior knowledge, skills and abilities and provide appropriate coaching.

A particular feature of such environments would be that learners could call upon *virtual characters* as authentic role models (based on *real people* that they value) as virtual teachers and companions.[16] These characters would not only be knowledgeable, but also carefully reflect the characteristics of people they model. Simulations and augmented reality will not only represent learning situations, but also allow learners to represent or model their own thoughts and responses, and those would be interpreted by the system.

We anticipate that by 2030 interactive simulations and representations will be *truly interactive* and *self-explanatory,* able to explain themselves to learners.[16, 104] For example, interactive instruments will observe numerical data via sensors and facilitate a seamless interplay between different kinds of knowledge, (qualitative, conceptual and quantitative) knowledge, and use whatever is available and needed for the situation at hand. Explanations will easily switch between kinds and use media, (video, audio and simulation), as required to induce student knowledge and understanding. The instruments would also adapt themselves to the knowledge, skills, abilities, interests and goals of the learner, and use flexible argumentation and communication styles as appropriate in a particular context.

Digital learning environments will become *highly motivating*. Learning systems will take into account the interests, intentions, and goals of students and will motivate them based on a student's age, economic, and cultural considerations; they will teach within practical/real-life contexts and include authentic role models as virtual learning companions and teachers.

By 2030 we suggest learners will have *expressive freedom* and the necessary tools to create powerful and expressive visual and diagrammatic representations.[16] Students will express their thoughts freely using pen and paper, or digital technologies and also other devices, seamlessly integrated and interconnected in the learning environment, particularly in terms of meaning. For example, in science and mathematics, students will use freehand drawing, sketches and diagrams in their attempts to solve problems. Similarly, environments with flexible representations will express knowledge and understanding of a domain through graphic drawings and sketches, thus enabling the assessment of students' knowledge.

We envision that by 2030, environments will provide truly individualized learning ...

We envision that by 2030, environments will provide *truly individualized learning* (optimized for the individual) capable of being *completely adaptive* and *adaptable* to a sufficiently complete representation of the learner (user model) in order to deliver the most optimized learning experience.[93, 16] Agents will determine the most optimized path to knowledge and skill acquisition for the desired learner outcome. For example, if a middle-school student is interested in tennis, then concepts taught in physics or mathematics will be presented in the context of tennis. If the student is interested in outer space, then lessons would be presented in this 'interest context.' Objects will take into account a full learner model that includes history, interests, age, previously successful learning methods, etc. that would all generally be considered as a part of the standard learner model. However, the complete model will also include heroes, role models, personal interests, and personal preferences used to create individualized and highly motivating environments tailored directly to the needs of students. This includes students with physical and/or cognitive disabilities.

Research Agenda for Intelligent Environments

Research is recommended for the various sensor modalities of intelligent environments. For example, research should develop *dialogue interfaces* for environments. Free-text and speech understanding currently is reliable only in dialogues where the computer asks short-answer questions or other questions where only a few types of easily detected responses are expected.[104] Yet this modality also includes understanding essays, reports, long explanations, and other monologues that have long, substantive content. These interfaces should become more reliable and accurate, including understanding students' typed- and spoken-input turns during dialogue, either amongst themselves or with a computer.[104] Advances in statistical language processing can help benefit understanding of both dialogue and monologue.

Improving *continuous speech recognition* is important for educational applications. What are student actions taken in immersive environments in which the computer does not need to recognize everything being said? What are student actions the computer can interpret as learning opportunities, e.g., those in which it may only need to detect who is talking and the learner's affect (via prosody) and length of their responses?

We also recommend research to *interpret student responses.* How do systems understand student input as it relates to the overall solution structure? How do they judge whether or not student actions are correct?[104] How can systems recognize learning opportunities? An apparently correct student action might be based on deep domain understanding, superficial reasoning or a correct guess! A given correct action may relate to more than one task subgoal and it can be unclear which subgoal the student is working on.[104] An action may map correctly to one task subgoal but be incorrect for the task subgoal the student is currently working on.

We recommend research on tools that automatically *adapt themselves* to fit the requirements of each learner. Research is needed on the *design, self-assembly* and *orchestration* of such tools. How *much knowledge* should these tools bring into a particular context and how much knowledge will they have access to, uch as learning goals of students and requirements brought forward by other stakeholders, parents and governmental institutes?[16] How do caretakers encode their *knowledge about sensitivity* to student characteristics, cultural contexts or special needs? How is *meta-data* created to describe the functions and purposes of each tool? Related issues address how to establish *benchmarks, standards* and *expected outcomes* to compare and organize learning instruments. How do instruments become orchestrated and communicate with each other? How do they self-improve and become more effective and efficient components?

Research is needed to ensure that *metadata descriptions* mean the same thing when used with different systems. One approach is to define central *ontologies* of learning objectives used to organize and index the systems. An alternative is the *folksonomy* approach, where structure emerges from decentralized tagging. Both approaches are in use and their relative merits are already being evaluated. Bringing the results of these analyses into educational systems research and recommending an educational systems architecture is an important challenge in the current time frame.

We recommend support for research on interactive simulations and representations that are able to *explain themselves* to learners.[16, 104] What is needed for continuous interaction between simulations and sensors, obtaining and potentially including new data? What is needed for seamless interplay between different kinds of knowledge, and representations thereof, such as qualitative, conceptual, causal, structural, and numerical (e.g., differential equations) representations? How do we address the communicative interaction, use multimedia, and switch modalities as appropriate to explain a phenomenon (what media is best suited for explaining what?) while also taking user characteristics into account (e.g., knowledge, skills, abilities, culture, general preferences and interests)? How can these systems be flexible while using multiple argumentation and communication styles?

We recommend that funders support research on how to classify instructional knowledge and skills, and establish indexes for retrieval, such that fragments of systems can be re-used and automatically assembled into a particular learning context.

We recommend that funders support research on how to *classify instructional knowledge* and *skills,* and establish indexes for retrieval, such that fragments of systems can be re-used and automatically assembled into a particular learning context.[16, 104] How can existing resources be re-used and how can a notion of (sufficient) cover of a domain be measured and established? How much and what kind of knowledge is needed for solving a certain problem? How can we establish interconnections and computer processable relationships between different kinds of knowledge (e.g., conceptual, subtype, qualitative, equations, consists-of) and also between different representations (e.g. rules, frames, XML, OWL)?

When the default boundaries of schools and other traditional educational institutes vanish due to abundant computer-based components, it will become important to create a meta-framework to reference new student achievements and goals.[16] How do we establish *benchmarks, standards,* and further means to *index* and *classify* educational materials, certificates, institutes, etc.? This implies funding research on techniques and mechanisms to manage *simultaneous* and *conflicting educational* goals, e.g., students learn the domain, remain interested, acquire a degree or certificate and/or develop self-esteem and social skills. How do we measure the effectiveness of educational systems using human experts, machine learning optimization and search mechanisms? How do we assess not only the final outcome of the systems, but also the process?

Research is needed to *standardize* approaches to knowledge *representation*. Such representations will accommodate low-level knowledge and skills as well as complex and metacognitive tasks and skills. A standardized representation of knowledge will become the framework that multiple systems can use. While it may be hard for educators within and between countries to agree on standard descriptions for complex knowledge and skills, the tools should map between them to assist researchers to recognize similar domain and teaching knowledge bases.

We also recommend that research address *knowledge engineering*. For example, cognitive task analysis (CTA) is a recognized bottleneck in the development of knowledge intensive systems. Often the CTA process uncovers latent knowledge within the domain that was previously unknown or untaught.

Regarding the larger issue of *trust* between humans and computers: How can we improve the quantity and quality of the communication between computers and humans? We recommend research to develop authoring tools (see below) that are desperately needed so that different segments of the community can repurpose educational systems to suit their particular needs and cultures.

We also recommend support for further development of technology begun in laboratories and now seemingly achievable in the short term, including deep and shallow *reasoning detectors*, mechanisms that detect the nature of student *activity pauses* (on-task thinking, on-task help-seeking, or off-task behaviors), interpreters that reason about the *intent* of student turns in *dialogue* and group collaborations, successful *"guess" detectors* (developed in math problem solving tutors) extended to other domains, and tools that *preserve ambiguous interpretations* for as long as possible.[104]

6. Educational Data Mining

Data from lifelong chronicling of student learning provides insight into how people learn, and suggests effective pedagogical strategies.

The sixth information technology that holds great promise for education is educational data mining (EDM) or methods for storing and reasoning about educational data and using it to better understand students' knowledge, to assess their progress, and evaluate the environments in which they learn. Data from lifelong chronicling of student learning provides insight into how people learn, and suggests effective pedagogical strategies. It provides knowledge about how to find clusters of children with similar problems, identifies success and failure in teaching strategies, and generates a deeper discernment of learning that has taken place. It sheds light on key questions in education and educational psychology.

School reform in the US depends on data management and mining. Under the American Recovery and Reinvestment Act, states must make assurances that they are building data systems to track student achievement and teacher effectiveness, in addition to adopting rigorous standards that prepare students for success in college and the workforce.

"Hopefully some day we can track kids from pre-school to high-school and from high school to college and college to career… Hopefully we can track good kids to good teachers and good teachers to good colleges of education."

— Arne Duncan, Remarks at the National Press Club, 1999

Distribution of well-managed and well-mined learning data is closely related to effective assessment of learning. Given a world where learners use a variety of electronic learning objects and those objects are continuously assessing learner progress on a variety of measures, it is possible to assess each individual across a wide variety of activities.[88] The distribution of assessment information to a broader variety of members of the educational establishment improves the odds that learners will succeed. For example, young learners could benefit from their parents being informed about learning deficiencies and providing additional help or motivation. Teachers might benefit from seeing a summary of areas of weakness of students in the class; such a report could guide teachers to immediately alter their teaching methods to accommodate student strengths and liabilities. Consideration of the social processes of learning will also affect the nature of data communication in connection with assessment of learning. Assessment will result in more effective, efficient, and enjoyable instruction when data technologies enhance the learner's experience and support network.[88] This highlights the importance of mechanisms that facilitate this communication of data in a way that is desired by and meaningful to stakeholders. Current pilot efforts such as TalkBank[58] and the DataShop from Pittsburgh Science of Learning Center[49] have been utilized for data from thousands of students coming from tens of projects; these efforts have already greatly increased access for interested researchers.

The Vision for Educational Data Mining

By the year 2030, we envision that educators will 'look at' diverse repositories of data wherever they may be and with sufficient processing power for any desired algorithm to process the data. Currently researchers often depend on computer programmers to overcome computing barriers between them and the data. Vast amounts of data on large numbers of students will be stored in public repositories and made available (in properly anonymized and analyzed form) to the broader research community. Data management of enormous files will be possible, perhaps by merging the capabilities of file systems to store and transmit built data from experiments, using logical organization of files, with specific query languages that enable analytic operations. Meta data will be available describing each experiment and the data it produced. The full power of relational databases will be available to allow effective interactions with the data. Interfaces will be available along with toolkits for purposes of visualizing and plotting the data.

Researchers will have developed a set of well-known and agreed upon tools and methodologies, much like research communities at the intersection of data mining and other scientific fields (e.g. bioinformatics). Researchers will draw upon standardized tools for data mining and machine learning to build models of student characteristics and behaviors, relate these characteristics and behaviors to one another and to external measures of interests (such as self-report instruments), study the effects of interventions on student behaviors in a fine-grained fashion, and develop tools for reporting the results of data mining analyses to key stakeholders such as teachers, school administrators, and parents.

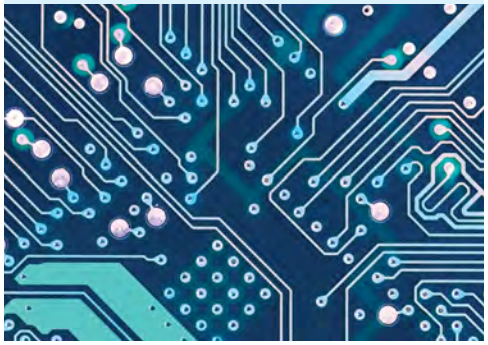
In turn, the educational data mining community will build on these resources to support researchers in each of the other areas described in this document. For example, user modeling will be facilitated by data-mined assessments of student learning and behavior; mobile learning will be facilitated by data-mined models of learners' context; social learning will be facilitated by social conversational agents based on rich models of student conversational behavior;[51] serious games, intelligent environments, and rich interfaces will use data-mined models to improve their adaptivity to individual differences among students.

Research Agenda for Educational Data Mining

As the variety of electronic learning objects grows, the likelihood of becoming drowned in details increases.

As the variety of electronic learning objects grows, the likelihood of becoming drowned in details increases. We recommend that research address this deluge of data, by developing new *data mining, security and database* techniques. Who are the potential consumers of this data, e.g., how can data be distilled for assessment content so it is useful for each stakeholder? Research is needed to develop data mining and management systems that provide frameworks for orientation and assessment materials, e.g., a shared data dictionary that prevents duplication of efforts and streamlines the use of nomenclature and categorization. Otherwise it will be extremely difficult to aggregate information across individual contributions. This envisioned taxonomy would first be established by corresponding researchers and then disseminated (and perhaps governed) by a body similar to other shared standards as coordinated by the IEEE or ISO.

To handle the deluge of data expected between now and 2030, data management projects will need to be significantly extended.



We recommend research to make data available to the broader research community, and for the greatest possible diversity of learning environments. Greater investment is needed to build open repositories for storing and sharing educational data. To handle the deluge of data expected between now and 2030, data management projects will need to be significantly extended. We recommend research to identify data management tools and repositories that can support the different data created. Furthermore, research is needed for development of broadly applicable tools that can support the types of analysis found to be most effective for educational data. While toolkits have been developed for general machine learning[109, 62] and for exploratory data analysis in education,[49] similar efforts have not yet been undertaken for large-scale educational data. Increasingly, top-quality educational data mining research relies upon methods for which there are no toolkits or for which toolkits have not yet been refined to a level where the broader research community can use them without support. For example, a method is needed for quickly labeling educational data to support supervised learning methods.[8] Other goals include variants on Bayesian knowledge tracing[7] that are increasingly used to study a wide variety of constructs; better tools for supporting statistical analysis of the differences between data mined models; and methods to generalize data-mined models across contexts.

Research is needed to develop *algorithms* particularly adapted to the educational domain and the unique characteristics of educational data. Recent research has found many benefits from integration between psychometric and machine learning methods; further funding for research in this direction, bringing together data miners and psychometricians, would be highly beneficial. In addition, recent work has often integrated the results of one model into a second model. For instance, models of learning have been key components in models of other constructs such as gaming the system.[6] Funding for determining how models and model-creation software can be made available for broader use of this nature, and for studying questions of validity and applicability of models within other models is likely to have a multiplier effect, making it easier to make effective models of a variety of constructs. Along similar lines, another area of significant promise for research funding is "discovery with models," in which a machine-learned model of a construct is developed and then utilized in a broader data set, in conjunction with other models or other measures (e.g. survey measures), in order to study the associations between the constructs studied. This type of research can be conducted quickly and inexpensively once the models have been developed and validated for generalizability.

7. Rich Interfaces

The seventh and final technology that holds great promise for education involves *rich interfaces* and *open-ended learning environments* that infuse new learning paradigms and resources into learning environments, effectively delivering ubiquitous instruction — anytime and anywhere.[19] Rich interfaces include technologies that sense, analyze and recognize human action, whether cognitive, metacognitive or affective. Sensors may include radio frequency identification (RFID), speech technologies, global positioning systems (GPS), smart phones, cameras (self cam, external cam), and longitudinal and comprehensive logging (MSR Vibe logger, socio-scopes). Virtual agents may include embodied and robotic creatures that may present as peers and offer engaging social support and advanced scaffolding. Rich interfaces will play a central role in defining key user characteristics, such as choice-adaptivity, ubiquity and wide accessibility, and support lifelong and lifewide learning. They will address novel feedback, such as exercise and mental health.

The scope of rich interfaces extends over multiple dimensions. They may be characterized as *problem solving environments* that span a wide variety of learning paradigms (e.g., intelligent tutors, exploratory simulations, multi-user collaborative systems, and game environments); *social interactions* that include multiple modalities (virtual agents with multiple roles, e.g., mentors, peers, learning companions, and teachable agents); *personalized interactions,* that attend to motivation, self-efficacy, and affect using adaptive media, information, and user models; and *mixed reality*, ranging from purely physical to purely virtual environments, and those that include both.[19] These dimensions are not independent or mutually exclusive, but provide a useful framework for characterizing research direction.

The Vision for Rich Interfaces

We envision that by 2030, rich interfaces will distinguish opportunities to improve student *affect* (motivation, interest, emotions, self-efficacy), "*21st century skills*" (teamwork, leadership, critical thinking, communication skills, etc.), and *learning styles* (prefers to explore or follow; likes video, visuals, or text).[19] Beyond their benefit to student assessment and data-mining activities (for evaluation of systems or treatment), rich interfaces will focus on learning opportunities that trigger changes in the course of the interaction with learners. Learning opportunities also include excellence that needs to be reinforced, ingredients that will be used later in learning events ("Just remember this, because we're going to discuss it later") and things that should be interesting to the student.

By 2030 we envision that students will complete quests in serious game environments,[87, 61] work in problem solving environments guided by

Technology will progress so that learners have access to a variety of learning resources through connected networks of learning management and educational systems, with some individual support in accessing learning resources...

coaches/companions,[21] and more generally make choices about different learning activities. Interface choices can be extremely informative in the assessment of student learning, and can provide mechanisms for mining student choices in relatively open learning environments to determine student patterns (optimal or otherwise) of learning.[88] Technology will progress so that learners have access to a variety of learning resources through connected networks of learning management and educational systems, with some individual support in accessing learning resources, taking part in formal and informal learning activities, and having opportunities to interact with peers and mentors. The next generation of widely accessible ubiquitous learning environments will develop rich interfaces that provide interoperability, and a seamless approach to bringing together learning content, personalized learning services, and the availability of a host of learning collaborators that span mentors, tutors, peers, and helpers.

Rich interfaces enable lifelong learning facilities that transcend traditional educational institutions (K-12 and university) and begin to impact aspects of continuing education and professional development as well as how to cope with changing situations in one's society and environment. Content, delivery, personalization, and choice adaptivity in the future will support seamless, ubiquitous access to lifelong learning facilities at home, at work, in schools and universities. This implies development of ways of organizing learning delivery that that go beyond course and program centric models to flexible and adaptive learner-centered, learner-controlled models of distributed lifelong learning.

We anticipate transformative advances in sensing devices, as summarized in Table 2, shown on the next page, that will allow interfaces to seamlessly capture user-relevant information and adapt to the user's needs.[19] Sensing devices will take advantage of the full spectrum of physiological data in order to maximize system ability to appropriately tailor to individual users. A broad array of feedback techniques will be available, including haptic, natural speech, novel interaction techniques and virtual simulation.[19] These interfaces will go beyond the traditional tutor model to include learning peers, (i.e., holistic "friends") encouraging lifelong learning though tactics that motivate learning and stimulate curiosity. Systems that measure students' affect will identify eureka moments, or moments of intrinsic interest or frustration.[88] They will measure 21st century skills, e.g., good teamwork, students' communication skills and good peer dialogues.

Interface Capabilities	2030 Vision
Affect & emotion Recognition	Strong recognition, fluent expression highly personalized
Embodied interactions	Full body capture everywhere; mirroring behavior
Learning companions	Virtual + robotic companions that seamlessly switch between virtual and physical settings
Brain-computer interfaces	Continuous wearable, fMRI-like capability' and EEG / Near Infra Red signals
Physiological	In-body monitoring and transmission – oxygen, glucose and cortisol indicators; HR/ Breath
Augmented Reality	Seamless, natural, ubiquitous, recognition
Haptic	Enhanced mobility, super hero capability high power haptic capabilities

Table 2: Vision of Rich Interface Capabilities

Rich interfaces will not be limited to virtual desktops in students' classrooms, but rather will expand into learners' environments, effectively delivering ubiquitous instruction — any time and anywhere.[19] These interfaces will address all factors that influence learning, including not only domain-related traditional feedback, but also affect, meta-cognition and mental health, to name only a few.

Research Agenda for Rich Interfaces

We recommend research to develop innovative interfaces (e.g., sensors, vision, object recognition and augmented manipulatives) that allow learners to move seamlessly between real and virtual environments. We recommend investigations into the educational settings and circumstances for which virtual environments are the best and most appropriate tools for learning. Can intelligent systems be responsible "companions" and partners for students? What is the role of teachers in relation to these environments? Are students free to work independently with systems and apart from classroom activities? Are we beginning to transfer control from teachers to computers? What are the privacy issues for students working on the Internet?

Research is needed to develop active learning components that accommodate full sensory input into any learning environment.[16] Sensors, object recognition, and augmented manipulatives will support active students in optimized learning environments. For example, students doing ecology projects at a wetland near their school will use virtual lab equipment and analyze water and soil samples projected into their augmented reality and used in the context of their ecological analysis. This scenario involves understanding the necessary multimedia and multimodal interfaces and how to design environments for flexible argumentation and communication styles.[16] Technological advancements are required in the field of vision, object and drawing recognition and in diagrammatic reasoning to have semantically aware and operationalized representations.

Rich interfaces will not be limited to virtual desktops in students' classrooms, but rather will expand into learners' environments, effectively delivering ubiquitous instruction — any time and anywhere.

We also recommend research to test and explore diverse technology presentations and paradigms.[19] *Gaming,* including emerging paradigms for augmented reality and lifelong gaming, offers new opportunities to advance mixed reality systems and explore diverse rule-based paradigms. *Simulations* provide opportunities for immersive understanding and adaptive exploration of diverse real world and constructed environments, thus affording a wide range of exploration opportunities, ranging from the scientific to the social and artistic. *Intelligent tutoring systems* are currently some of the most advanced rich interfaces and will continue to be a driving force of rich interfaces. *Embodied, situated cognition and mind-body learning* include rich interfaces and tangible media that provide compelling opportunities to expand the important role of these learning modalities. *Exploratory environments* (sandbox): *open exploratory environments* (especially those developed through participatory design) are strategies that stimulate curiosity, exploration, and creativity. *Holodecks* are a paradigm of fully adaptive rich interface environments that are compelling and will continue to provide a powerful educational potential. *Teachers and mentors* receive new developmental opportunities to participate in diverse roles through rich interfaces and their diverse deployment scenarios. *Experiences, scenarios and projects* with rich interfaces offer terrific and limitless opportunities for developing new and ubiquitous experiences for learning, including diverse scenarios, topics, social structures and engagement.

Conclusions

We expect major changes in education as a result of evolving education technology and learning environments. Specifically, lifelong learning facilities will transcend traditional educational institutions and begin to impact aspects of continuing education and professional development. Content, delivery, personalization, and adaptivity of instructional systems will support seamless, ubiquitous access to lifelong learning facilities at home, at work, in schools and universities. Changes in education will deliver new ways of organizing learning delivery that go beyond course and program-centric models and include flexible and adaptive learner-centered, learner-controlled models of distributed lifelong learning.

Personalized learning will be supported by tools that enhance student experience, reflection, analysis, and theory development: most of all we expect systems to lead to rich experiences that incorporate opportunities for learners to reflect on their own learning. Likewise learning scientists will have new opportunities to analyze vast new data sets collected from rich databases. These will contain elements of learning, affect, motivation, and social interaction, and will trace patterns of learning and engagement over lifetimes, leading to new theory developments with powerful impacts. Learners have the opportunity for one-on-one instruction from embodied, ambient, and embedded virtual agents; co-located and distributed human peers and mentors; community members, teachers, and parents, each enhanced by information from rich interfaces and diverse sources of guidance for providing actualizing social and motivational feedback opportunities and interactions. Creativity, curiosity, and intrinsic motivation will be enhanced as people have increased opportunities through personal constructionist project-based activities that apply a framework of using information technology to collect, relate, create, and donate. Longitudinal and lifelong learning will be enhanced: just as we expect these interfaces to permeate throughout life experiences, we expect tools and interfaces will support lifelong learning (longitudinal), and ubiquitous (embedded) experiences. Persistent interfaces will adapt to learners across life transitions and stages. In many ways they may come to know the learners better than learners know themselves. As a tool they will be there to enhance and facilitate learners' life aspirations, reflections, and engagements.

Social learning will be supported by tools that provide new opportunities for interactions of motivated learners. Intelligent tutoring systems with affective learning companions sense and respond appropriately to elements of learners' emotional and motivational states.[4]

Diminishing boundaries or blurring of formal and informal learning will happen as tools and resources used in formal environments become widely available. Emerging examples of this phenomenon exist in the form of LEGO Mindstorms robotics interfaces that are used in museums, classrooms, homes, and play. Likewise, the Scratch-programming environment (http://scratch.mit.edu/) offers tools that span formal and informal environments. The seamless transition of learners, and learners' abilities to transfer, apply, and enhance their knowledge, experience, and discovery and imaginative inquiry across environments, also helps to diminish boundaries.

Enhancing the role of stakeholders will be supported when teachers become significant in informal as well as formal settings and interact with students in broader and more diverse contexts. Teachers acting as administrators will be supported by tools and interfaces that provide new and more accurate forms of information about individual and group learning, motivation, social activity, and opportunities, and will respond more effectively to a greater range of needs of increasingly diverse learners. Teachers as participants will engage side-by-side with students, as members of project teams and at times as followers of student leaders. Teachers as pedagogues will have more tailored and higher quality information to inform their actions and greater range of actions. Teachers interacting with special needs children will have ready access to and specific guidance from the latest and best strategies for specific students, stemming from advances in educational psychology. These technologies will also empower teachers with new tools and targeted opportunities to directly apply these advanced theories, e.g. understanding and applying Dweck's message, that the mind is like a muscle and that even though the task may be frustrating, sticking with it may be a learning opportunity. Students, likewise, will engage in diverse participatory roles as leaders, followers, public speakers, listeners, integrators, decision makers, supporters and contributors. Students as pedagogues will contribute to their peers and increase their social skills and networks, as well as solidifying and expanding their learning.

> ***... all learners have the potential to be more successful, and that rich interfaces will play an important role in both helping individuals be more successful and in helping advance learning science.***

As the world and its challenges become increasing complex we see the need and opportunity for rich interfaces, new forms of learning and social and creative interaction as paramount to societies' success.[19] Today, many students succeed yet many others fail; we believe all learners have the potential to be more successful, and that rich interfaces will play an important role in both helping individuals be more successful and in helping advance learning science. If we do not adopt the new strategies afforded by rich interfaces even students succeeding today will likely fail to meet tomorrow's challenges. Thus, these rich interface tools and learning environments provide not only the opportunity to extend the success of today's and tomorrow's successful students, but promise to increase the success rate, providing education and opportunity for all learners.

Participants in Global Resources for Online Education

The GROE Project extends its appreciation to the following individuals who led, supported, contributed, and assisted in producing the material in this report. They gave of their valuable time and offered their creative ideas and energy. We especially thank the coordinators and contributors listed below whose service on behalf of the Project was provided without monetary remuneration.

Project Leader

Beverly Park Woolf, *University of Massachusetts*

Group Coordinators

Ryan Baker, *Carnegie Mellon University*
(Data Mining and Management)
Bert Bredeweg, *University of Amsterdam*
(Intelligent Systems)
Winslow Burleson, *Arizona State University*
(Rich Interfaces)
John Leslie King, *University of Michigan*
(Policy)
Rose Luckin, *London Knowledge Lab*
(Social Learning)
Valerie Shute, *Florida State University*
(Assessment)
Daniel Suthers, *University of Hawai'i at Manoa*
(Social Learning)
Emma Tonkin, *UKOLN, University of Bath*
(Mobile Learning)
Kurt VanLehn, Arizona State University
(Intelligent Systems)

Contributors

Ivon Arroyo, *University of Massachusetts*
Paul Bacsich, *Sero Consulting*
Amy Baylor, *National Science Foundation*
Joseph Beck, *Worcester Polytechnic Institute*
Gautam Biswas, *Vanderbilt University*
Kristy Boyer, *North Carolina State University*
John Carney, *Carney, Inc.*
Robert Christopherson, *Arizona State University*

David Cooper, *University of Massachusetts*
Albert Corbett, *Carnegie Mellon University*
Sharon Derry, *University of Wisconsin-Madison*
Toby Dragon, *University of Massachusetts*
Art Graesser, *University of Memphis*
Camilla Jensen, *Arizona State University*
Lewis Johnson, *Alelo, Inc.*
Ian Jones, *University of Nottingham*
Judy Kay, *University of Sydney*
Henry Kelly, *Federation of American Scientists*
Dave Kuntz, *Pragmatic Solutions*
Chad Lane, *USC/Institute for Creative Technologies*
James Lester, *North Carolina State University*
Roy Levy, *Arizona State University*
Diane Litman, *University of Pittsburgh*
Manolis Mavrikis, *London Knowledge Lab*
Kasia Muldner, *Arizona State University*
Chris Quntana, *University of Michigan*
Sowmya Ramachandran, *Stottler Henke Associates Inc.*
Nora Sabelli, *SRI International*
Mark Schlager, *Microsoft*
Michael Timms, *WestEd*
Jody Underwood, *Pragmatic Solutions*
Susan Winter, *National Science Foundation*
Diego Zapata, *Educational Testing Service*

Computing Research Association (CRA)

Andrew Bernat, *Executive Director*

Liaison to the Computing Community Consortium (CCC)

John Leslie King, *University of Michigan*

Project Assistant

Burt Woolf, *University of Massachusetts*

Credits

Photographs: Winslow Burleson, TakWei Chan, David Cooper, Rose Luckin, Carla Gomez Monroy, Mike Sharples, Stephen Woolf and *One Laptop Per Child*

References

All references in this report are numbered in the text and listed below, alphabetically by author.

1. Aleven, V. and Koedinger, K. R. (2000). "Limitations of Student Control: Do Students Know When They Need Help?*" Conference on Intelligent Tutoring Systems,* Berlin: Springer-Verlag.
2. Anderson, J. R. (1983). *The Architecture of Cognition,* Cambridge, MA, Harvard University Press.
3. Arroyo, I. and Woolf, B. P. (2005). "Inferring Learning and Attitudes from a Bayesian Network of Log File Data," *Twelfth International Conference on Artificial Intelligence in Education*. Looi, C. K. McCalla, G., Bredeweg, B. and J. Breuker, (eds.) Amsterdam.
4. Arroyo, I., Cooper, D., Burleson, W., Woolf, B. P. Park, Muldner, K., Christopherson, R. (2009). "Emotion Sensors go to School," Conference on Artificial Intelligence in Education.
5. Baker, R. S. J. D. (2007). "Modeling and Understanding Students' Off-Task Behavior in Intelligent Tutoring Systems," Proceedings of ACM CHI 2007: Computer-Human Interaction: 1059-1068.
6. Baker, R. S. J. D., Corbett, A. T., Roll, I., Koedinger, K. R. (2008). "Developing a Generalizable Detector of When Students Game the System," *User Modeling and User-Adapted Interaction: 183*, 287-314.
7. Baker, R. S. J. D., Corbett, A.T., Aleven, V. (2008). "Improving Contextual Models of Guessing and Slipping with a Truncated Training Set." Proceedings of the 1st International Conference on Educational Data Mining: 67-76.
8. Baker, R. S. J. D., Corbett, A. T., Wagner, A. Z. (2006) "Human Classification of Low-Fidelity Replays of Student Actions," Proceedings of the Educational Data Mining Workshop at the 8th International Conference on Intelligent Tutoring Systems, 29-36.
9. Beal, C. R. (1994). *Boys and Girls: The Development of Gender Roles*, New York, McGraw Hill.
10. Becher, T. (1987). *The Disciplinary Shaping of the Profession*, Berkeley, CA, University of California Press.
11. Bird, A. (1994). "Careers as Repositories of Knowledge: A New Perspective on Boundaryless Careers," *Journal of Organizational Behavior* 15(4): 325.
12. Biswas, G., Leelawong, K., Schwartz, D., Vye, N. and The Teachable Agents Group at Vanderbilt (2005). "Learning by Teaching: A New Agent Paradigm for Educational Software," *Applied Artificial Intelligence 19:* 363-392.
13. Black, P. and William, D. (1998). "Inside the Black Box: Raising Standards Through Classroom Assessment," *Phi Delta Kappan: 80(2),* 139-148.
14. Böck, M. (2004) "Family Snaps: Life Worlds and Information Habitus," *Journal of Visual Communication 3(3),* pp. 281–293
15. Bransford, J., Brown, A. L. and Cocking, R. R. (1999). *How People Learn: Brain, Mind, Experience, and School,* Washington, DC, National Academy Press.
16. Bredeweg, B., Arroyo, I., Carney, C., Mavrikis, M. and Timms, M. (2009). "Intelligent Environments," Global Resources for Online Education Workshop, Brighton, UK.
17. Bruner, J. (1973) *Going Beyond the Information Given*, New York, Norton.
18. Bruns, A. (2007). "Beyond Difference: Reconfiguring Education for the User-Led Age," *ICE3: Ideas in Cyberspace Education: Digital Difference*, Ross Priory, Loch Lomond.
19. Burleson, W., Biswas, G., Muldner, K., Baylor, A. (2009). "Rich Interfaces — 20 Year Horizon," Global Resources for Online Education (GROE), Tempe Arizona.

20. Cetintas, S., Si, L., Xin, Y. P., Hord, C. and Zhang, D. (2009). "Learning to Identify Students' Off-Task Behavior in Intelligent Tutoring Systems," Conference on Artificial Intelligence in Education.

21. Chou, C., Chan, T. W., Lin, C. J. (2003). "Redefining the Learning Companion: The Past, Present, and Future of Educational Agents," *Computers & Education Archive,* Volume 40, Issue 3

22. Collins, A. and Stevens, A. L. (1983). "A Cognitive Theory of Inquiry Teaching," *Instructional-Design Theories and Models: An Overview of Their Current Status*. C. M. Reigeluth. Hillsdale, N.J., Erlbaum: 247-278.

23. Cook, J., Bradley, C., Lance, J., Smith, C. and Haynes, R. (2007) "Generating Learning Contexts With Mobile Devices." In Pachler, N. (ed.), *Mobile Learning: Towards A Research Agenda,* WLE Centre for Excellence, London

24. Csikszentmihalyi, M. (1990). *Flow, the Psychology of Optimal Experience*. New York, NY, Harper Perennial.

25. de Jong, T. and van Joolingen, W. (1998). "Scientific Discovery Learning with Computer Simulations of Conceptual Domains," *Review of Educational Research.*

26. Dede, C. (2009). "Learning Context: Gaming, Simulations and Science Learning in the Classroom," National Research Council Committee for Learning Science: Computer Games, Simulations, and Education.

27. Derry, S. J., Levin, J. R., Osana, H., Jones, M. S. and Peterson, M. (2000). "Fostering Students' Statistical and Scientific Thinking: Lessons Learned From an Innovative College Course," *American Educational Research Journal 37:* 747-773.

28. Dillenbourg, P. (1999). "What do You Mean by 'Collaborative Learning?'" In Dillenbourg, P. (ed.), *Collaborative Learning: Cognitive and Computational Approaches* (pp. 1-19). Amsterdam: Elsevier.

29. Dragon, T. and Woolf, B. P. (2007*).* "Understanding and Advising Students from Within an Inquiry Tutor," Conference on Artificial Intelligence in Education, Workshop on Inquiry. Marina del Ray, CA.

30. Duncan, A., (1999). Excerpts from Secretary Arne Duncan's Remarks at the National Press Club, from http://www.ed.gov/blog/2009/06/excepts-from-secretary-arne-duncan's-remarks-at-the-national-press-club/.

31. Fischer, K. and Granoo, N. (1995). "Beyond One-Dimensional Change: Parallel, Concurrent, Socially Distributed Processes in Learning and Development," *Human Development* 1995 (38): 302-314.

32. Greeno, J., Collins, A., and Resnick, L. B. (1996). "Cognition and Learning," *Handbook of Educational Psychology*. R. Calfee and D. Berliner. New York, MacMillan.

33. Greer, J., McCalla, G., Cook, J., Collins, J., Kumar, V., Bishop, A. and Vassileva, J. (1998). "The Intelligent HelpDesk: Supporting Peer Help in a University Course," Conference on Intelligent Tutoring Systems, 1998, San Antonio, Texas.

34. Hamilton, E., and Feenberg, A. (2005). "The Technical Codes of Online Education," *E-Learning* 2(2): 104-121.

35. Inkson, K. (2007*). Understanding Careers: The Metaphors of Working Lives*. Thousand Oaks: Sage Publications.

36. Ivanic, R. and Tseng, M. L. (2005). *Understanding The Relationships Between Learning and Teaching: An Analysis of the Contribution of Applied Linguistics*. London, NRDC.

37. Jameson, A. (1996*).* "Numerical Uncertainty Management in User and Student Modeling: An Overview of Systems and Issues," *User Modeling and User-Adapted Interaction 5* (3/4): 103-251.

38. Jermann, P., Soller, A., and Lesgold, A. (2004). "Computer Software Support for CSCL," *What we Know About CSCL*. J. W. Strijbos, Kirschner, P. A., Martens, R.L., Kluwer Academic Publishers: 141-166.

39. Johns, J. and Woolf, B. P. (2006). "A Dynamic Mixture Model to Detect Student Motivation and Proficiency," Conference on Artificial Intelligence (AAAI-06). Menlo Park, CA, AAAI Press: 2-8.

40. Johnson, D. W. and Johnson, R. T. (1994). "An Overview of Cooperative Learning," *Creativity and Collaborative Learning.* J. Thousand, Villa A., and A. Nevin. (eds.) Baltimore, MD, Brookes Press.

41. Johnson, D. W. and Johnson, R. T. (1989). *Cooperation and Competition: Theory and Research*. Edina, MN, Interaction Book Company.

42. Johnson, R. T. and Johnson, D. W. (2005). The Cooperative Learning Center at the University of Minnesota, Newletter 2006, from http://www.co-operation.org/index.html.

43. Jones, A., Issroff, K., and Scanlon, E. (2007). "Affective Factors in Learning with Mobile Devices," *Big Issues in Mobile Learning,* M. Sharples, LSRI, University of Nottingham: 17-22.

44. Kay, J., Maisonneuve, N., Yacef, K., and Reimann, P. (2006). "The Big Five and Visualizations of Team Work Activity," Conference of Intelligent Tutoring Systems, Taiwan.

45. King, J., Sabelli, N., Kelly, H. (2009). "Preamble on Policy Issues," Global Resources for Online Education (GROE) Workshop, Tempe Arizona.

46. Kleinberg, J. (2008) "The Convergence of Social and Technological Networks," *Communications of the ACM, Volume 51, Issue 11*, pp. 66-72.

47. Kling, R. (2000). "Learning About Information Technologies and Social Change: The Contribution of Social Informatics," *The Information Society* 16(3): 217-232.

48. Kobsa, A., ed. (2007). "The Adaptive Web: Methods and Strategies of Web Personalization," *Lecture Notes in Computer Science,* New York, Springer-Verlag.

49. Koedinger, K., Cunningham, K., Skogsholm A., Leber, B. (2008) "An Open Repository and Analysis Tools for Fine-Grained, Longitudinal Learner Data," Proceedings of the 1st International Conference on Educational Data Mining, 157-166.

50. Kress, G. and Pachler, N. (2007) "Thinking about the 'm' in m-learning," in Pachler, N. (ed.) *Mobile Learning: Towards a Research Agenda.* London: WLE Centre, Institute of Education, London.

51. Kumar, R., Gweon, G., Joshi, M., Cui, Y., Rosé, C. P. (2008). "*Supporting Students Working Together on Math with Social Dialogue,"* SLaTE Workshop on Speech and Language Technology in Education.

52. Lampert, M. (2001). *Teaching Problems and the Problems of Teaching*. New Haven, CT, Yale University Press.

53. Laurillard, D. (2007) "Pedagogical Forms for Mobile Learning," in Pachler, N. (Ed.) *Mobile Learning: Towards A Research Agenda.* London: WLE Centre, Institute of Education, London.

54. Laurillard, D., Kolokitha, M., Mellar, H., Selwyn, N., Noss, R. (2008*).* "Learning Through Life: The Role of Technology," *Foresight Report,* Office of Science and Innovation, London Knowledge Lab, Institute of Education, University of London.

55. Lave, J., and Wenger, E. (1991). *Situated Learning: Legitimate Peripheral Participation*. Cambridge: Cambridge University Press.

56. Luckin, R., Dragon, T., Lane C., Jones, I. (2009). "Social Learning and Gaming," Global Resources for Online Education, (GROE) Brighton, UK.

57. MacKeracher, D. (2004). *Making Sense of Adult Learning*. Toronto, University of Toronto Press.

58. MacWhinney, B., Bird, S., Cieri, C., Martell, C. (2004). "Talkbank: Building an Open Unified Multimodal Database of Communicative Interaction," Conference on Language Resources and Evaluation.

59. McArthur, D., Lewis, M. and M. Bishay (1994). "The Roles of Artificial Intelligence in Education: Current Progress and Future Prospects," RAND DRU-472-NSF.

60. Mercer, N., and Littleton, K. (2007). *Dialogue and the Development of Children's Thinking: A Sociocultural Approach,* Taylor & Francis e-Library.

61. Michael, D., and Chen, S., (2005) *Serious Games: Games That Educate, Train, and Inform*, Muska & Lipman/Premier-Trade

62. Mierswa, I., Wurst, M., Klinkenberg, R., Scholz, M. and Euler, T. (2006). "YALE: Rapid Prototyping for Complex Data Mining Tasks," 12th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining (KDD 2006), 935-940.

63. National Center for Educational Statistics (2009). *Digest of Educational Statistics,* Chapter 2, http://nces.ed.gov/fastfacts/display.asp?id=64

64. Nii, H. P. (2009). "Expert Systems Building Tools: Definitions," http://www.wtec.org/loyola/kb/c3_s2.htm

65. Pachler, K. (2007). "Mobile Learning Towards a Research Agenda," *Leading Education and Social Research,* 1-96.

66. Pachler, N. (2009) "Pedagogical Issues and Mobile Learning," presentation at AERA 2009.

67. Papatheodorou, C. (2001). *Machine Learning in User Modeling in Machine Learning and its Applications,* Springer Berlin / Heidelberg.

68. Papert, S. (1980) *Mindstorms: Children, Computers and Powerful Ideas,* New York, Basic Books

69. Price, S. and Rogers, Y. (2003) "Let's Get Physical: The Learning Benefits of Interacting in Digitally Augmented Physical Spaces," in Underwood, J. and Gardner, J. (Eds), *Computers and Education: 21st Century Learning, 43*, pp.137–151.

70. Price, S., ed. (2007). "Ubiquitous Computing: Digital Augmentation and Learning," in *Mobile Learning: Towards a Research Agenda.* London, WLE Center for Excellence.

71. Randell, C., Price, S., Rogers, Y., Harris. E. and Fitzpatrick, G. (2004) "The Ambient Horn: Designing A Novel Audio-Based Learning Experience," *Personal and Ubiquitous Computing,* 8, 3, pp.144–161

72. Resnick, Martin, M., F. Sargent, R. and Silverman, B. (1996) "Programmable Bricks: Toys to Think With," *IBM Systems Journal* 35, pp.3–4.

73. Rogers, Y. and Price, S. (2006) "Using Ubiquitous Computing to Extend and Enhance Learning Experience," in Mark van'T Hooft and Karen Swan (eds.), *Ubiquitous Computing in Education: Invisible Technology, Visible Impact* Mahwah, NJ, Lawrence Erlbaum Associates

74. Royer, J. M., and Garofili, L., eds. (2005). "Explaining Gender Differences in Mathematics Performance," in Kaufman, J. and Gallagher, A. (Eds.), *Gender Differences in Mathematical Cognition.* London: Cambridge University Press. (pp. 99-120)

75. Russell, S. J., and Norvig, P., (2002) *Artificial Intelligence: A Modern Approach,* Prentice Hall, 2nd edition, 2002.

76. Salomon, G., ed. (1993). *Distributed Cognitions: Psychological and Educational Considerations*. Cambridge: Cambridge University Press.

77. Scardamalia, M., and Bereiter, C. (1991). "Higher Levels of Agency for Children in Knowledge Building: A Challenge for the Design of New Knowledge Media," *The Journal of the Learning Sciences, 1* (1), 37-68.

78. Shapiro, S. (1992). *Encyclopedia of Artificial Intelligence: 2nd Edition.,* John Wiley & Sons.

79. Sharples, M. E. (2007). "Big Issues in Mobile Learning," Workshop by Kaleidescope Network of Excellence Mobile Learning Initiative. Nottingham, University of Nottingham.

80. Shulman, L. S. (1986). "Those Who Understand: Knowledge Growth in Teaching," *Educational Searcher* 15(2): 4-14.

81. Shute, V. J. and Zapata-Rivera, D. (2007). "Adaptive Technologies," *Handbook of Research on Educational Communications and Technology*, Spector, J. M., Merrill, D., van Merrienboer, J. and Driscoll, M. (eds.) Mahwah, NJ, Erlbaum.

82. Shute, V. J. (2008). "Focus on Formative Feedback," *Review of Educational Research* 78 (1): 153-189.

83. Shute, V. J. (in press). "Stealth Assessment in Computer-Based Games to Support Learning," to appear in Tobias, S. and Fletcher J. D. (eds.), *Computer Games and Instruction.* Charlotte, NC, Information Age Publishers.

84. Shute, V. J. and Glaser, R. (1990). "Large-Scale Evaluation of an Intelligent Tutoring System: Smithtown," *Interactive Learning Environments, 1*, 51-76.

85. Shute, V. J. and Towle, B. (2003). "Adaptive E-Learning," *Educational Psychologist*, 38(2), 105-114.

86. Shute, V. J., Hansen, E. G., and Almond, R. G. (2008). "You Can't Fatten a Hog by Weighing it—or Can You? Evaluating an Assessment for Learning System Called ACED," *International Journal of Artificial Intelligence and Education*, *18*(4)*, 289-316*.

87. Shute, V. J., Ventura, M., Bauer, M. I., and Zapata-Rivera, D. (2009). "Melding the Power of Serious Games and Embedded Assessment to Monitor and Foster Learning: Flow and Grow," in Ritterfeld, U., Cody, M. and Vorderer, P., (eds.), *Serious Games: Mechanisms and Effects* (pp. 295-321). Mahwah, NJ, Routledge, Taylor and Francis

88. Shute, V. J., Zapata, D., Kuntz, D., Levy, R., Baker, R., Beck, J., Christopher, R., (2009) "Assessment: a Vision," Global Resources for Online Education (GROE), Tempe Arizona.

89. Shute,V. J., Glaser, R. and Raghavan, K. (1989). "Inference and Discovery in an Exploratory Laboratory," in Ackerman, P. L., Sternberg, R. J. and Glaser, R. (eds.), *Learning and Individual Differences* (pp. 279-326). New York, NY, W.H. Freeman.

90. Simon, H. (1997). "What We Know About Learning," speech presented at the 1997 Frontiers in Education Conference.

91. Sison, R. and Shimura, M. (1998). "Student Modeling and Machine Learning," *International Journal of Artificial Intelligence in Education* 9: 128-158.

92. Slavin, R. E. (1990). *Cooperative Learning: Theory, Research, and Practice*, Englewood Cliffs, NJ, Prentice-Hall.

93. Smith, K. A., Sheppard, S.D, Johnson, D. W. and Johnson, R. T. (2005). *"Pedagogies of Engagement: Classroom Based Practices," Journal of Engineering Education* 94(1): 87-101.

94. Soller, A., Martinez-Monez, A., Jermann, P. and Muehlenbrock M. (2005). "From Mirroring to Guiding: A Review of State of the Art Technology For Supporting Collaborative Learning," *International Journal Of Artificial Intelligence In Education 15*(4): 261-290.

95. Soller, A., Wiebe, J., and Lesgold, A. (2002). "A Machine Learning Approach to Assessing Knowledge Sharing During Collaborative Learning Activities," Conference on Computer Support for Collaborative Learning (CSCL 2002)

96. Stahl, G. (2003). "Meaning and Interpretation in Collaboration," Conference on Computer Support for Collaborative Learning Support for Collaborative Learning (CSCL 2003), Bergen, Norway.

97. Stiggins, R. J. (2002). "Assessment Crisis: The Absence of Assessment for Learning," *Phi Delta Kappan Professional Journal 83*(10): 758-765.

98. Stiggins, R. J. (2006). "Assessment for Learning: A Key to Motivation and Achievement," *Edge: The Latest Information for the Education Practitioner 2*(2): 1-19.

99. Suthers, D. D. (2006*).* "Technology Affordances for Intersubjective Meaning-Making: A Research Agenda for CSCL," *International Journal Of Computer Supported Collaborative Learning, 1*(3), 315-337.

100. Suthers, D. D., Connelly, J., Lesgold, A. M., Paolucci, M., Toth, E. E., and Toth, J. (2001). "Representational and Advisory Guidance for Students Learning Scientific Inquiry," in Forbus K. D. and Feltovich P. J. (eds.), *Smart Machines in Education: the Coming Revolution in Educational Technology* (pp. 7-35). Cambridge, Massachusetts: AAAI Press, The MIT Press.

101. Suthers, D. D., Toth, E. and Weiner, A. (1997). "An Integrated Approach to Implementing Collaborative Inquiry in the Classroom," Conference on Computer Supported Collaborative Learning (CSCL '97), Toronto.

102. Suthers, D., Derry, S., Schlager, M. and Quntana, C. (2009). "Social Learning," Global Resources for Online Education (GROE), Tempe Arizona.

103. Toffler, A., (1971) Forward to *Rethinking the Future: Rethinking Business, Principles, Competition, Control and Complexity, Leadership, Markets, and the World,* Rowan Gibson (ed.), London, Nicholas Brealey

104. VanLehn, K., Corbett, A., Ramachandran, S., Underwood, J., Jensen, C. (2009). "Intelligent Virtual Environments," Global Resources for Online Education (GROE), Tempe Arizona.

105. Vassileva, J. (1998). "Goal-Based Autonomous Social Agents Supporting Adaptation and Teaching in a Distributed Environment," *Conference on Intelligent Tutoring Systems,* Goettl, H. H. B., Redfield, C. and Shute., V. (eds.) San Antonio, Texas, Springer Verlag, 1452: 564-573.

106. Vygotsky, L. S. (1978). *Mind in Society: The Development of Higher Psychological Process,* Cambridge, MA, Harvard University Press, (Originally published 1930, Oxford University Press, New York).

107. Webb, G., Pazzani, M. and Billsus, D. (2001). "Machine Learning for User Modeling," in *User Modeling and User-Adapted Interaction, 11:* 19, 29, Netherlands.

108. Wilensky, U., Stroup. W. (1999). "Learning Through Participatory Simulations: Network-Based Design for Systems Learning in Classrooms," Conference on Computer Support for Collaborative Learning, Palo Alto, California.

109. Witten, I. H. and Frank, E. (2005) *Data Mining: Practical Machine Learning Tools and Techniques*, San Francisco, Morgan Kaufmann.

110. Woolf, B. P. (2009). *Building Intelligent Interactive Tutors: Student-Centered Strategies for Revolutionizing E-Learning*, San Francisco, CA, Elsevier Publishing Morgan Kauffman.

111. Zyda, M. (2005). "From Visual Simulation to Virtual Reality to Games," *IEEE Computer*

The following is the formal bibliographic citation for the **NETP** referenced throughout this report:

Transforming American Education: Learning Powered by Technology, the National Educational Technology Plan 2010, a draft of which was released by the Office of Educational Technology in the US Department of Education dated March 5, 2010. The document can be found at http://www.ed.gov/technology/NETP as of May, 2010. The document is referred to in this report as NETP.